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Physiopathology and Pathology of Spinal Injuries in Aerospace Medicine

(Second Edition)

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(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

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PHYSIOPATHOLOGY AND PATHOLOGY OF SPINAL INJURIES IN AEROSPACE MEDICINE

(Second Edition)

by

R.P.Delahaye and R.Auffret

with the collaboration of

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(Contributions to Chapter 4)

CONTENTS

CHAPTER 1 - INTRODUCTION

The Significance of Spinal Disorders in Aerospace Medicine

In the introduction to AGARDograph AG 140.70 "Physiopathology and Pathology of Affections of the Spine in Aerospace Medicine" (1970) (52), we noted that the aviation doctor was confronted almost daily with problems of spinal pathology in flight personnel. Moreover, the most contradictory opinions found in numerous medical and technical reports do not ease the task of the clinician. In fact, he can consult a variety of research studies and a few articles or reviews which deal with the clinical aspects of spinal disorders in the aviator and specify the course to follow (52, 97).

What is the situation in 1980? The incidence of backache (96, 177) and of spinal trauma has not decreased. Some new clinical entities have been defined; in-flight fractures in pilots of combat aircraft caused by high frequency vibrations (although these are rare); spinal injuries in parachutists manoeuvring in "relative" work. Despite improvements in systems, other disorders continue to pose problems both from their incidence and their severity: fractures of the dorso-lumbar spine in pilots after ejection from combat aircraft; backache in helicopter pilots.

Without any doubt, clinicians have contributed through epidemiological, clinical and radiological studies, to the better understanding of spinal disorders in aerospace medicine. Unfortunately, it appears that the same cannot be said of fundamental or applied research. In particular, attempts to improve mathematical models of the spinal column have been little known to physicians and clinicians, despite major financial investments. This deficiency - these failures - should not surprise them, considering the ignorance that still exists today of elementary or detailed knowledge of spinal physiology and biodynamics.

We do not claim that all these studies were, are, or will be useless. However, on the basis of the essential criteria of cost effectiveness, doubt appears justified. Divorced from their clinical and radiological context and their practical application (prevention of traumatic spinal injuries, or the standardisation of a more or less rational regime of therapy, for example), these theoretical studies are not very useful, and have little influence in the practical field.

These remarks, which are based upon experience, justify (if justification is needed) the requirement for work by a team which combines clinicians, radiologists, surgeons, and specialists from aeromedical centres (physicians, pilots, engineers).

In the editing of this book, which was directed by Roland Paul Delahaye and Robert Auffret, we have employed a team which consists of physicians and technicians of the Dominique Larrey (78013 Versailles) and the Begin (94160 Saint Mande) hospitals, of the Aerospace Medicine Laboratory, Flight Test Centre, (Centre d'Esais en Vol) Bretigny sur Orge, and of the Military Aeromedical School. Accustomed to working together for more than twenty years, this aeromedical group has treated and followed the clinical progress of numerous pilots with spinal disorders and has examined them to assess their fitness to fly or to determine rates of compensation. These detailed evaluations were ordained by the Principal Flight Personnel Medical Evaluation Centre, Paris, or by the Secretariat General of Civil Aviation (Ministry of Transport).

The Aerospace Medicine Laboratory of the Flight Test Centre evaluates all new equipment brought into service and gives an opinion after tests which employ the most advanced techniques. Commissions which include pilots, clinicians and investigators systematically study all accidents at the request of official bodies.

This AGARDograph cannot be an exhaustive study of all the disorders of the spinal column which occur in aviation medicine. Rather, it is a guide which simultaneously calls on clinical experience, evaluation, the results of applied research carried out by the editorial team, and data provided by detailed analysis of the literature on the subject.

We wish to thank the Aerospace Medical Panel, its Chairman, and the Publications Committee for having renewed their confidence in us for the preparation of this manual, which should be of use both to the physician and to the pilot.

We are conscious of the honour of this assignment, which is based essentially on the recognised value of the studies presented to various scientific sessions at meetings of the Aerospace Medical Panel, and of the research carried out in our hospital facilities and in French military laboratories.

In the opening chapters, we shall review the basic anatomy and physiology of the spinal column, with particular emphasis on the currently accepted biodynamic data. We shall then analyse the stresses of flight that affect the spine. These chapters seem to us to be essential to an understanding of the different clinical varieties of spinal disorder in aerospace medicine.

This book comprises three parts of very unequal importance. The incidence, aetiology, symptomatology and development of traumatic lesions require very precise study. Postural disorders of unknown physiopathogenic origin deserve our attention, for these new problems have not yet been completely explained. Acquired spinal disease, especially in older pilots, requires study because its incidence is not decreasing.

It seems necessary to deal with the fundamental problem of management of a spinal disorder, whether it is acquired, traumatic or inflamatory, at two particular stages in the life of a pilot; during the examination for selection, and during fitness testing as his flight career develops.

Disorders of the spinal column raise medico-legal problems which are often very difficult to resolve. Is arthritis post-traumatic? Is "infectious rheumatism" (ankylosing spondylitis or rheumatoid polyarthritis) related to violent trauma occurring in an accident, or to repeated "micro-traumas"? Spondylolisthesis discovered during a flying career raises two problems. Can it be attributed to the flying task, or to in-flight trauma? Can lesions, known to exist at the start of a flying career, develop further?

In the bibliography, we cite the various works consulted in editing this book. They include many European references, the originality and priority of which are undeniable, because recent-studies of the subject are more numerous in the English-speaking countries. The references comprise, on the one hand, those which deal with spinal disorders in aerospace medicine and, on the other, those concerned only with the study of the spine itself.

Roland Paul DELAHAYE

Robert AUFFRET

30 July 1980

CHAPTER 2 - ANATOMY OF THE SPINE

C. Kleitz and R.P. Delahaye

SUMMARY

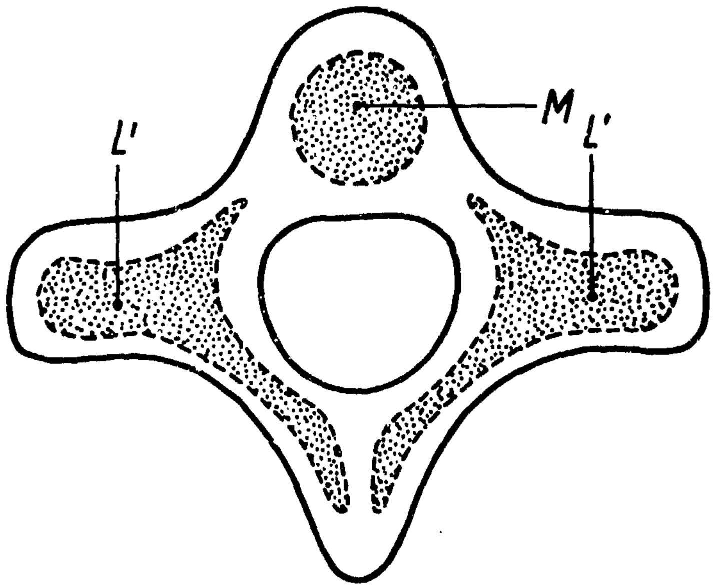


Figure 1. Foetal vertebra at the beginning of ossification of the cartilaginous unit (after Testut, 442). M = Medial centre for the body, L[1] = Lateral centres.

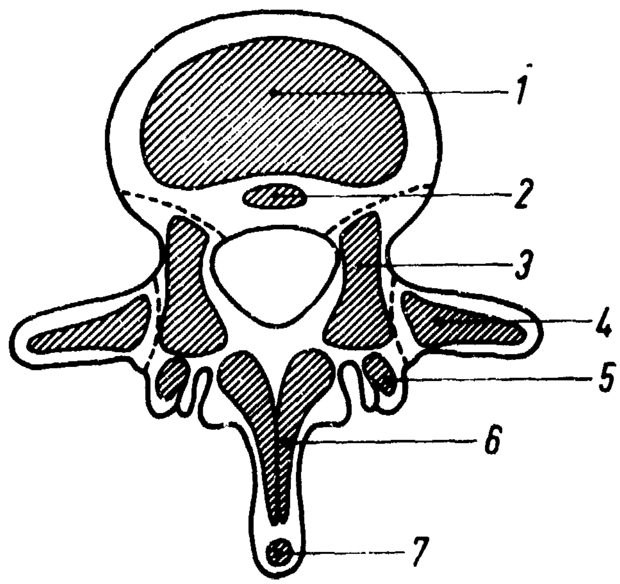


Figure 2. Ossification and development of a lumbar vertebra - plan view (after Paturet).

1. Primary centre of vertebral body
2. Secondary centre
3. Anterior neural centre
4. Costal centre
5. Transverse centre
6. Posterior neural centre
7. Secondary spinous centre

The spinal column is a long, tough and flexible bony stem, located in mid-line of the posterior part of the trunk. It extends from the head, which it supports, to the pelvis, which supports it. It encloses and protects the spinal cord, which lies in the spinal canal.

The column is divided into bony units; the vertebrae, which are articulated one upon the other. The spine exhibits a number of curves. Because of this it has the properties of support of the trunk, shock-absorption, and mobility associated with a positive stability.

The spine consists of 24 presacral vertebrae (7 cervical, 12 dorsal or thoracic, and 5 lumbar), the sacrum and the coccyx.

2.1. EMBRYOLOGY OF THE SPINE (307, 326, 416, 442)

In the embryo, a membranous spinal column develops axially around the notochord. In time, this is succeeded by a cartilaginous column made up of discrete metameric protovertebrae. The cartilaginous stage is followed by ossification arising from primary and secondary nuclei (Fig. 1).

The primary nuclei contain an anterior primary centre and two lateral sites for the neural arches which will later produce extensions to form the articular and transverse processes and the laminae. They appear towards the middle of the third month of intra-uterine life.

The secondary nuclei develop towards the eight month, in the form of upper and lower marginal rings for each vertebral body (Figs. 2, 3). These are the marginal laminae, which fuse with the body of the vertebra at about the age of 14 or 15.

2.2. GENERAL CHARACTERISTICS OF THE VERTEBRAE

Each vertebra consists of two parts (Fig. 4); a rounded anterior vertebral body and a posterior arch which, with the posterior portion of the body, encloses the vertebral or spinal foramen through which the spinal cord passes.

2.2.1. The vertebral body has the form of a cylindrical segment; its upper and lower surfaces, which are composed of spongy tissue, lie horizontally. The circumference is covered by a cortex and is depressed in its median part. The posterior segment, in contact with the vertebral canal, is concave in the transverse axis.

The major portion of a vertebral body, which is surrounded by a thin layer of compact bone, is formed of spongy tissue the trabecular structure of which is visible in sections and in radiographs. The bony fibrils cross, to form a complex network in which three distinct trabecular systems can be distinguished in the adult:

- a radial horizontal system (persistence of the primitive radial system)

- a vertical system which extends through the entire spine, creating an architectural unit having the function of support

- an oblique system comprising two bundles which extend over the posterior arch; a superior oblique bundle and an inferior oblique bundle (Figs. 5, 6).

2.2.2. The posterior arch is formed by the pedicles in front and by the vertebral laminae behind (Fig. 4). Seven processes are inserted upon it:

- the pedicles are located on each side of the posterior face of the vertebral body and are flattened transversely; their notched edges, with those of the vertebrae immediately above and below, surround the intervertebral foramina

- the flattened quadrilateral laminae close the vertebral foramen posteriorly

- the spinous process arises from the junction of the laminae and is directed posteriorly; it is flattened transversely, and its apex is free

- the transverse processes are inserted laterally behind the pedicles

- the articular processes, four in number, lie vertically and are inserted at the junction of the pedicles and the laminae: the superior and inferior processes on the same side articulate with those immediately below and above; they form a small vertical bony column which runs on each side of the spinal canal.

2.3. SPECIAL REGIONAL CHARACTERISTICS OF VERTEBRAE

The dimensions of the vertebrae increase from the head toward the pelvis, in proportion to the weight which they have to support.

The vertebrae of the cervical, thoracic, lumbar, sacral and coccygeal segments each have their own characteristics which are particularly marked in the middle of each region. These characteristics are modified towards the extremities of each segment, so that the transition from one type to another is gradual.

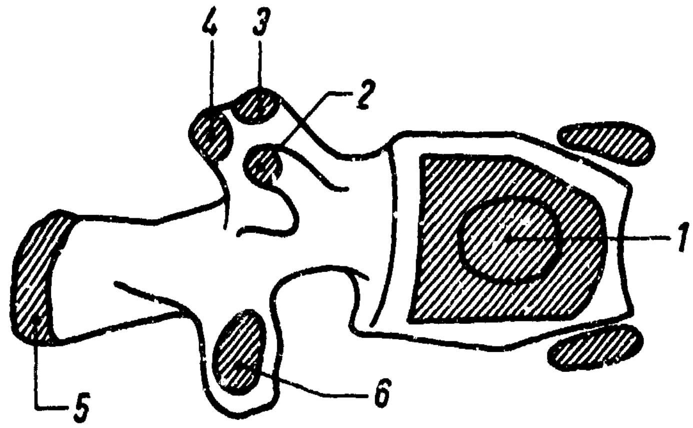


Figure 3. Ossification and development of a lumbar vertebra - lateral view (after Paturet).

1. Primary centre of body
2. Subsidiary transverse centre
3. Subsidiary centre (superior articular process)
4. Subsidiary centre (mamillary tubercle)
5. Secondary spinous centre
6. Subsidiary centre (inferior articular process)

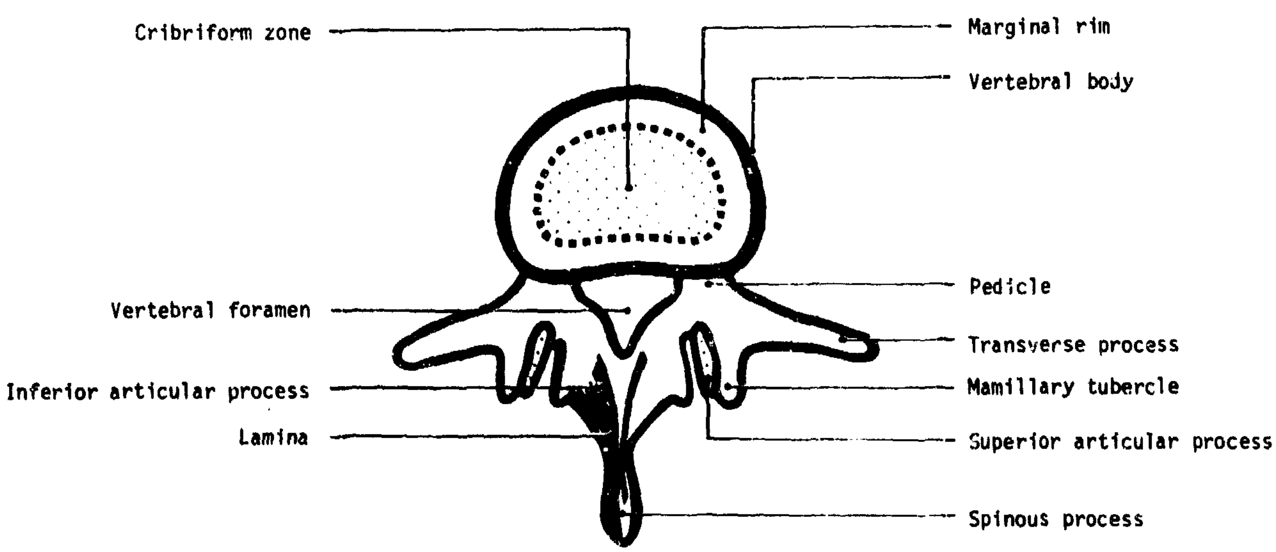


Figure 4. Morphology of thoracic or lumbar vertebra (after Paturet).

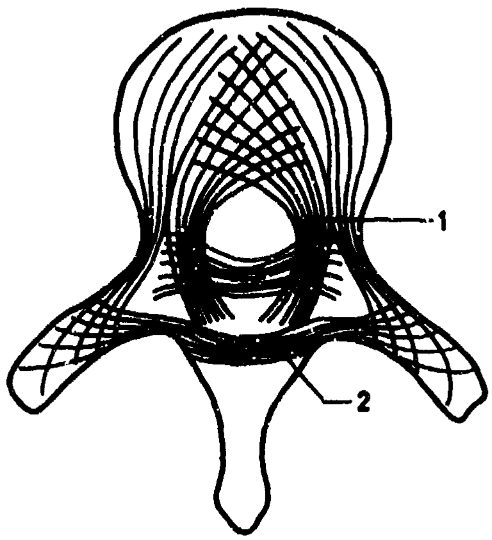


Figure 5. Architecture of a vertebra, from above (after Gallois & Japiot, 442).

1. Oblique fasciculus
2. Inter-transverse fasciculus

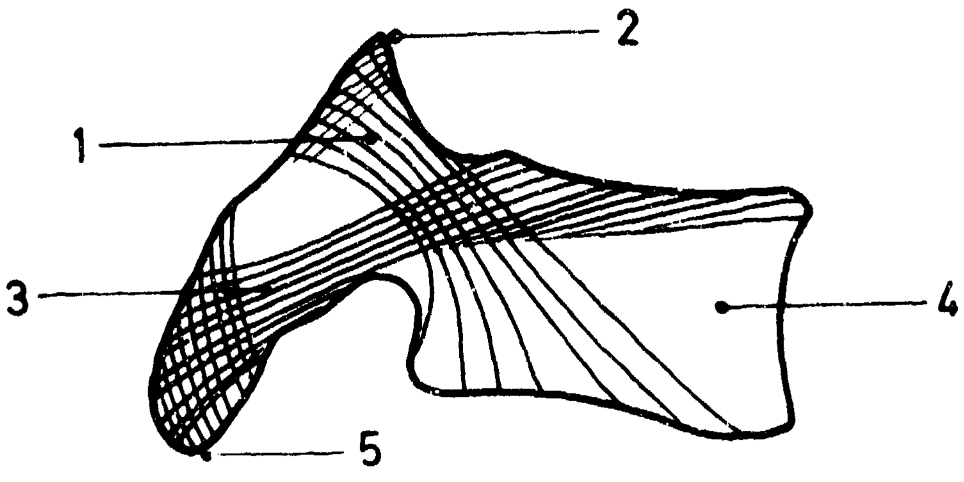


Figure 6. Architecture of a vertebra - lateral view (after Gallois & Japiot, 442).

1. Superior oblique fasciculus
2. Superior articular process
3. Inferior oblique fasciculus
4. Equatorial vascular zone
5. Spinous process

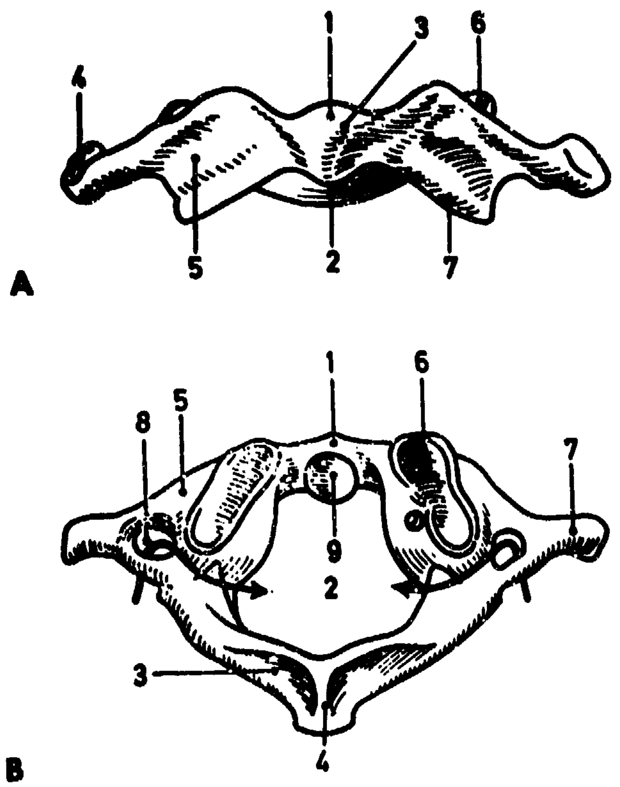


Figure 7. a) Atlas - Anterior view

1. Anterior arch
2. Posterior arch
3. Anterior tubercle
4. Transverse process
5. Lateral masses
6. Superior articular facets (glenoid cavities)
7. Inferior articular processes

(after Testut, 442)

b) Atlas - From above

1. Anterior tubercle
2. Foramen
3. Posterior arch
4. Posterior tubercle
5. Lateral masses
6. Superior articular facets (glenoid cavities)
7. Transverse process
8. Foramen for vertebral artery (arrow indicates its path)
9. Articular facet for odontoid process

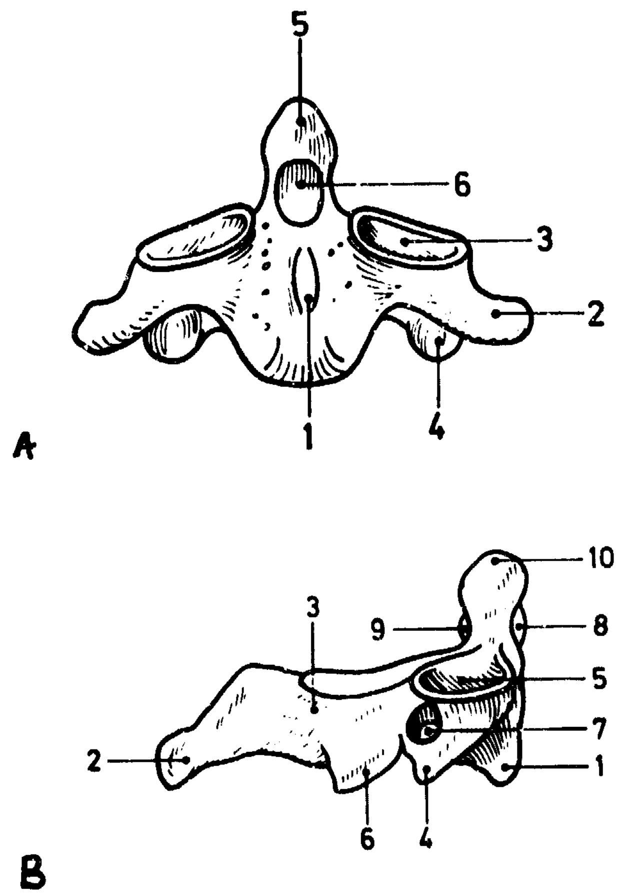


Figure 8. a) Axis - Anterior view

1. Body
2. Transverse process
3. Superior articular process
4. Inferior articular process
5. Odontoid process
6. Articular facet for anterior arch of atlas

b) Axis - Left lateral view

1. Body
2. Spinous process
3. Lamina
4. Transverse process
5. Superior articular process
6. Inferior articular process
7. Foramen for vertebral artery
10. Odontoid process with (8 & 9) its articular facets

(after Testut, 442)

2.3.1. The Cervical Vertebrae

2.3.1.1. The Two First Cervical Vertebra Have a Special Morphology.

The atlas is formed of two arches (Fig. 7).

- an anterior arch, the inner surface of which articulates with the anterior face of the odontoid process

- a posterior arch.

Arising at the level of each pedicle are:

- a superior articular facet, which is concave and articulates with the occipital condyle

- an inferior facet which is horizontal and convex, and articulates with the superior facet of the axis vertebrae, to permit rotational movement of the head.

The axis vertebra (Fig. 8) is unique in having a body surmounted by the odontoid process. Its inferior articular facets match the shape of those of the vertebra immediately below it.

2.3.1.2. From C3 to C7 (Fig. 9) each vertebral body has two lateral prominences on its superior surface; the unciform processes. The transverse processes are inserted by two roots which, with the pedicle, surround the foramen through with the vertebral artery passes.

The spinous process has a bifid tip, and flat articular facets; the superior ones facing upwards and backwards and the inferior downwards and forwards. The vertebral foramen is triangular with its apex posteriorly.

2.3.2. The thoracic vertebrae (Figs. 10, 11) have a thicker body. Close to the insertion of the pedicle on each side are two articular facets, superior and inferior, which are designed to articulate with the head of the ribs. The spinous process is long and slopes downwards and backwards. Each transverse process has a costal facet which corresponds to the tubercles of the ribs. The superior articular process faces backwards and outwards, and the inferior one forwards and inwards. The vertebral foramen is circular.

2.3.3. The lumbar vertebrae have large, kidney shaped bodies with the major axis transverse. The pedicles, which are thick and lie horizontally, are inserted over half the vertebral body, at the junction of the lateral and posterior surfaces. The spinous process is rectangular, thick, and horizontal. The transverse processes, also called the costiform processes, are long. The superior articular processes are flattened transversely, and have a projection (the mamillary tubercle) on their outer surfaces.

The inferior processes have a convex articular surface which faces outwards and forwards, and slides in the concavity of the superior articular process of the vertebra immediately below. The vertebral foramen is triangular in section.

2.3.4. The sacrum and the coccyx are downward extensions of the spine. They are articulated together and curved, with the concavity towards the front. While the sacrum is the result of fusion of five sacral vertebrae, the coccyx is formed by the fusion of between four and six degenerate vertebrae the size of which decreases from top to bottom. Their form is thus that of a truncated pyramid flattened from front to back, with its base uppermost and its apex at the bottom.

The base of the sacrum faces upwards and forwards. Its middle portion is formed by the upper face of the body of the first sacral vertebra, while its lateral parts form wings, behind which lie the superior articular processes, and whose surface faces inwards and backwards. The sacral canal, which encroaches upon the posterior wall of the sacrum, extends and ends the vertebral foramen (Figs. 13, 15).

2.4. INTERCONNECTIONS AND ARTICULATIONS

All the vertebrae are joined together by three elements; the intervertebral disc, and the anterior and two posterior articulations. These are reinforced by systems of powerful ligaments (Figs. 12 and 13). The intervertebral joints are similar in all parts of the spinal column, with the exception of the first cervical vertebra which articulates with the head, and of the lumbo-sacral joint. We shall treat these in a separate section after considering first the anterior and then the posterior articulations.

2.4.1. Anterior Interconnections

The vertebral bodies are articulated between their superior and inferior surfaces. The joints consist of intervertebral discs and peripheral ligaments.

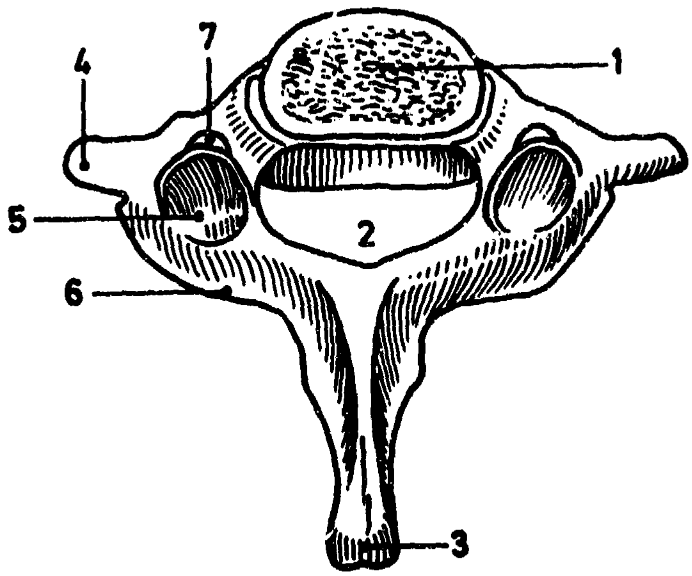


Figure 9. Seventh cervical vertebra - from above.

1. Body
2. Foramen
3. Spinous process
4. Transverse process
5. Superior articular process
6. Lamina
7. Vertebral artery foramen

(after Testut)

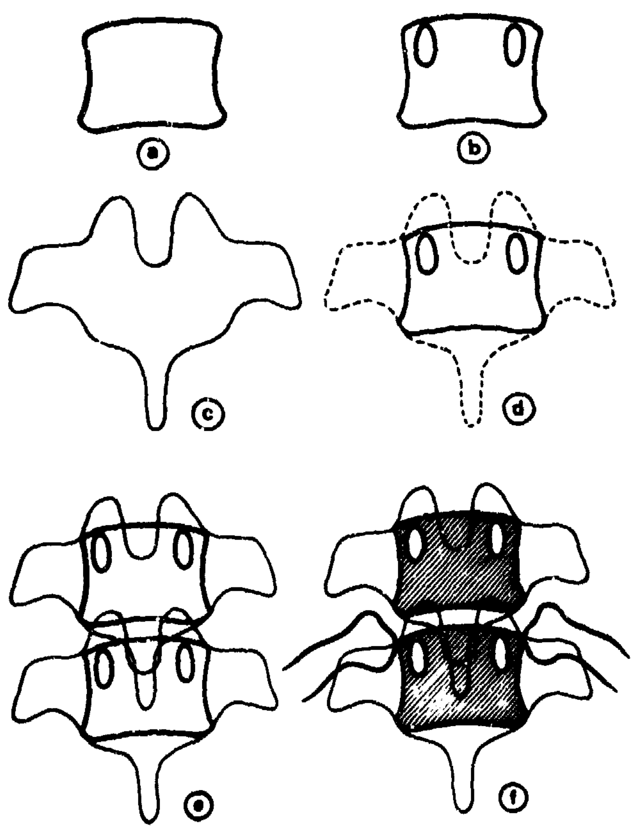


Figure 10. Thoracic vertebrae - from the front

(from radiograms)

a) Body
b) Body and pedicles
c) Posterior arch
d) Vertebra
e) Connection of 2 vertebrae
f) Costo-vertebral articulation (normal incidence)

(after Delahaye & Jolly)

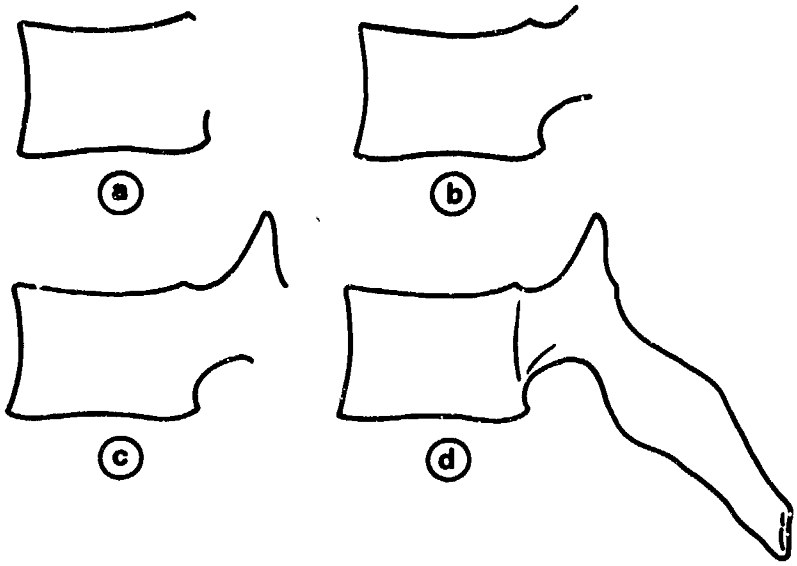
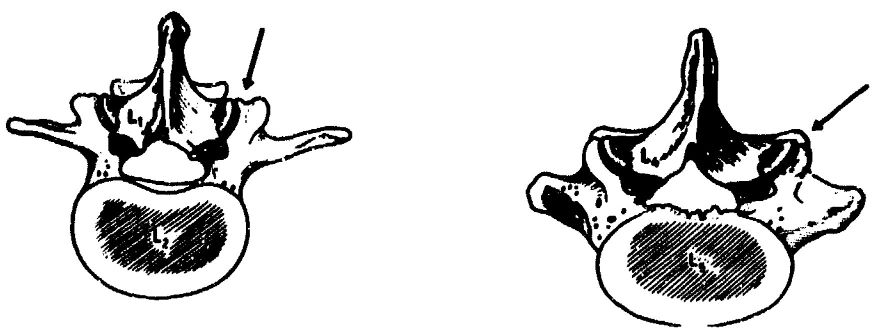


Figure 11. Eighth thoracic vertebra - lateral view (from radiograms) (287).

a) Body
b) Body and pedicles
c) Body and pedicles and superior articular processes
d) Body and pedicles and superior articular processes and spinous processes



A B

Figure 12. Orientation of apophyseal articulations.

a) Upper surface of body of L2, from above. The posterior arch of L1 has been left in place, but its pedicles cut and its body removed to show better the orientation of the apophyseal articulations.

b) Upper surface of body of L5, from above. The posterior arch of L4 has been left in place, but its pedicles cut and its body removed to show better the orientation of the apophyseal articulations. The direction is very different from the preceding case.

(after Coliez, 288)

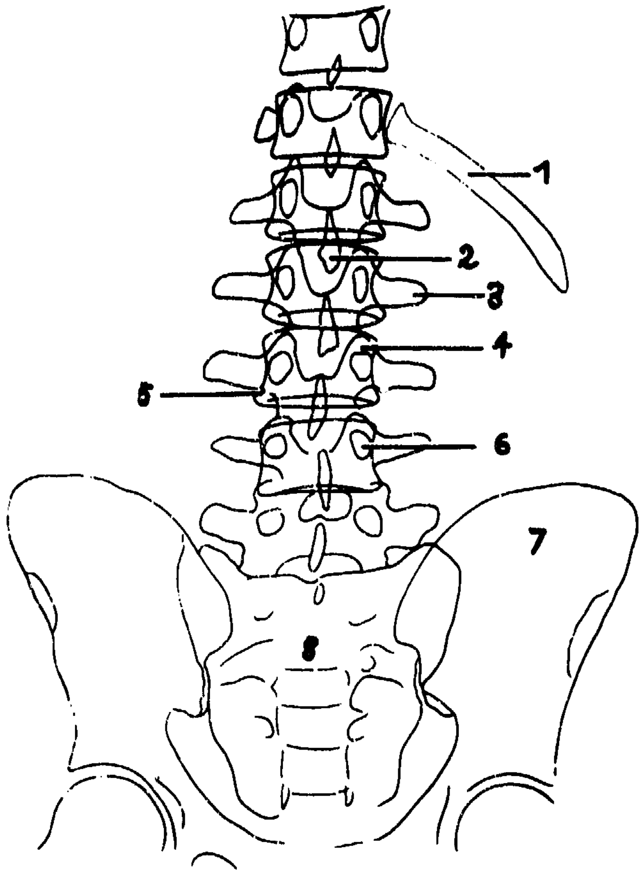


Figure 13. Tracing of radiogram of entire lumbar spine (postero-anterior plate)

1. Twelfth rib
2. Spinous process
3. Transverse process
4. Superior articular process of L3
5. Lamina
6. Pedicle
7. Iliac wing
8. Sacrum

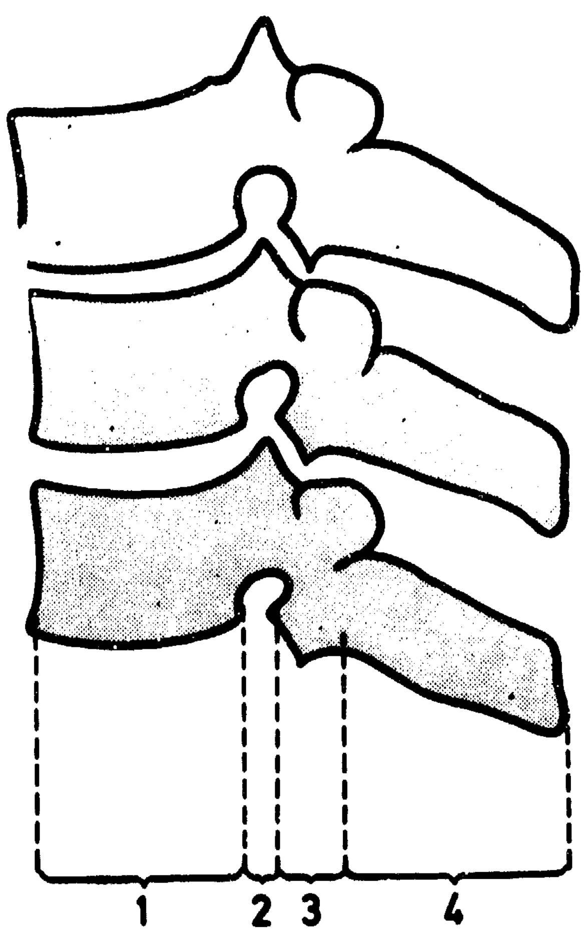


Figure 14. Lateral view of spine (after Coliez, 288)

1. Column of bodies and discs
2. Column of pedicles and spinal canal
3. Column of apophyseal masses
4. Spinous processes

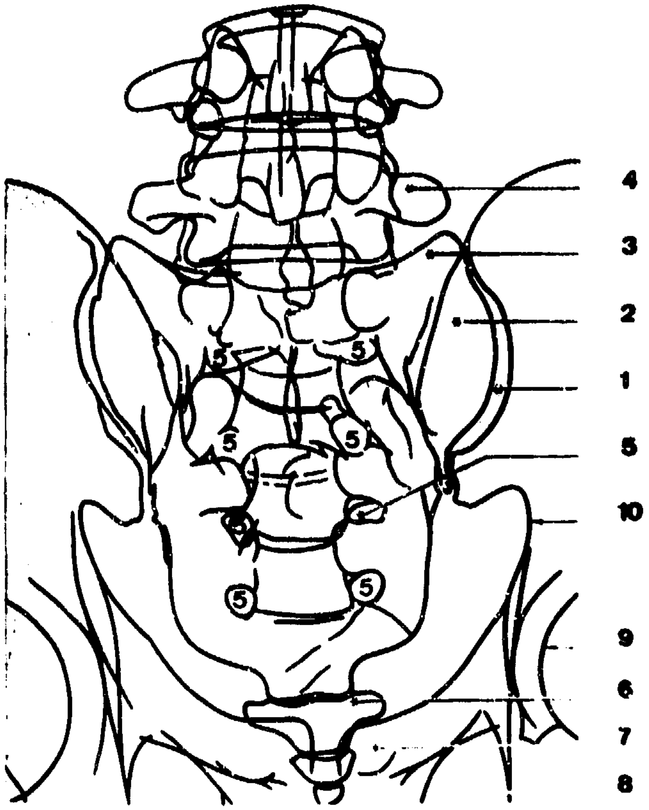


Figure 15. Sacrum

1. Sacro-iliac interface
2. Tuberosity of ilium
3. Wing of sacrum
4. Transverse process of L5
5. Sacral foramen
6. Coccyx
7. Pubis
8. Obturator foramen
9. Head of femur
10. Innominate line

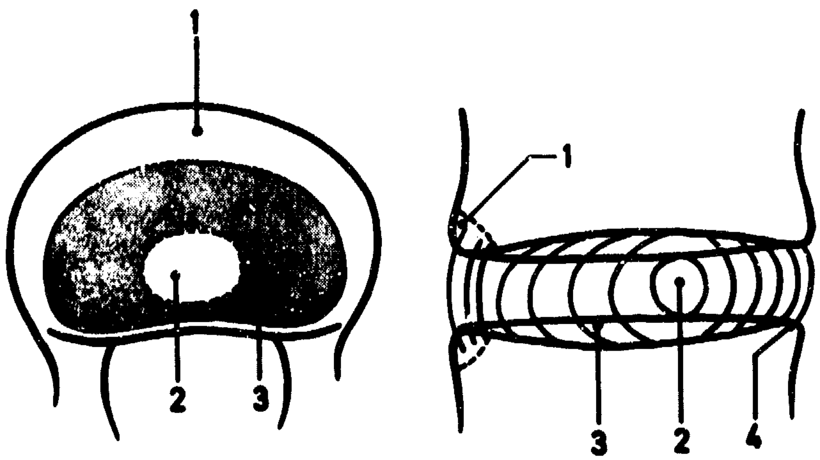


Figure 16. Intervertebral disc.

1. Margin
2. Nucleus pulposus
3. Left: cribiform zone
   Right: cartilaginous plate
4. Posterior vertebral border

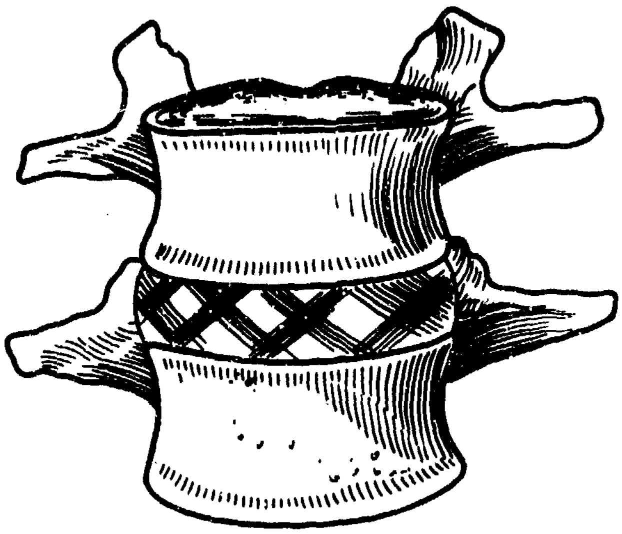


Figure 17. Lumbar intervertebral disc (anterior aspect).

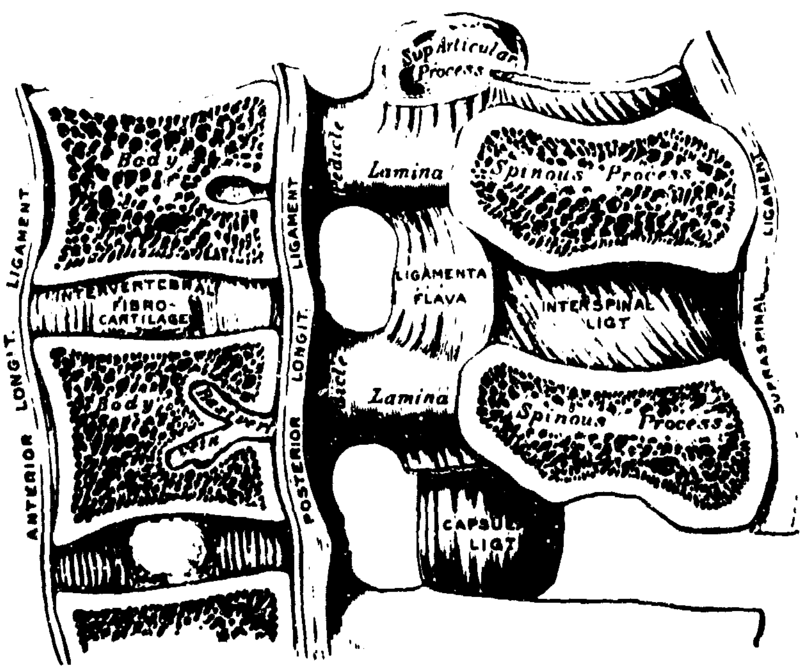


Figure 18. Cross-section of two lumbar vertebrae, with ligaments (from Epstein, 307).

2.4.1.1. Intervertebral Discs (Figs. 16, 17)

The intervertebral discs occupy the spaces between the vertebral bodies and have the shape of a biconvex lens the faces of which conform with and are attached to the articular surfaces of the vertebrae.

The height of the discs slowly decreases from the cervical column, where it is uniform (2-4 mm), to the fifth thoracic vertebra. It then gradually increases again towards the base of the spine and reaches its greatest dimension between L4 and L5 (on average 12 mm) only to decrease again between L5 and S1.

The intervertebral disc comprises two parts; one central, the nucleus pulposus, and the other peripheral, the annulus fibrosus (Figs. 16 and 17).

The nucleus pulposus occupies 50-60% of the cross section of the disc. It is an oval gelatinous mass situated in the central portion of the disc closer to the posterior border than to the anterior. It is composed of cells resembling chondrocytes dispersed in an intracellular matrix of collagen fibrils and aggregates of mucopolysaccharide, which gives the nucleus its great capacity for absorbing and holding water (251, 377). Depending upon the age, it contains 90-75% water (439).

The annulus fibrosus is made up of concentric laminae formed mainly of collagen fibres attached above and below to the vertebral bodies. The fibres in the interior of each lamina are arranged obliquely between the vertebrae in successive layers. These lie perpendicular to each other and are firmly joined by an intercellular cement. The anterior part of the annulus is twice as thick as the posterior part. There is less cement posteriorly. The fibres of the innermost layers of the annulus fibrosus pass into the nucleus and connect with the intercellular matrix. There is no clear demarcation between the annulus and the nucleus, but there is a zone of transition.

2.4.1.2. Peripheral Ligaments (Figs. 18, 19, 20)

These comprise two fibrous bands which extend throughout the length of the spine, one in front and the other behind. They are called the anterior and posterior longitudinal ligaments.

The anterior longitudinal ligament descends on the anterior face of the column from the basilar process of the occiput to the anterior surface of the sacrum. It is attached to the intervertebral disc and to the vertebral bodies. It is made up of long superficial fibres and short deeper fibres which unite adjacent vertebrae.

The posterior longitudinal ligament is situated on the posterior surface of the bodies and the discs. Its lateral borders are serrated and it is wider at the level of the discs than at the middle of the bodies. It also is made up of two types of fibre.

2.4.2. Posterior Articulation (307, 326, 331, 416, 442)

These also comprise joints and ligaments.

2.4.2.1. The joints of the articular processes. In each of these joints the inferior articular process of a vertebra is connected to the superior articular process of the vertebra situated below it. The articular facets are flat in the cervical and thoracic regions, and are segments of a cylinder in the lumbar region. Their orientation differs according to the level.

2.4.2.2. The ligaments (Figs. 20, 21, 22). The yellow ligaments, which are thick and very strong, unite the laminae. They are joined together in the median line. Their anterior surface is in contact with the dura mater.

The interspinous ligaments are thin membranes which fill the space between two spinous processes.

The supraspinous and subspinous ligament is a fibrous band which extends throughout the length of the spine. It is attached to the apices of the spinous processes. In the neck, it is much expanded and has the form of a triangular fibrous sheet.

2.4.3. Interconnections at the Extremities of the Spine

2.4.3.1. The First Two Cervical Vertebrae

The atlas is connected to the occiput by two atlanto-occipital joints. On each side of the foramen magnum, the concave elliptical surface of the lateral mass of the atlas is articulated to an occipital condyle. Two powerful ligaments reinforce these anterior and posterior atlanto-occipital joints.

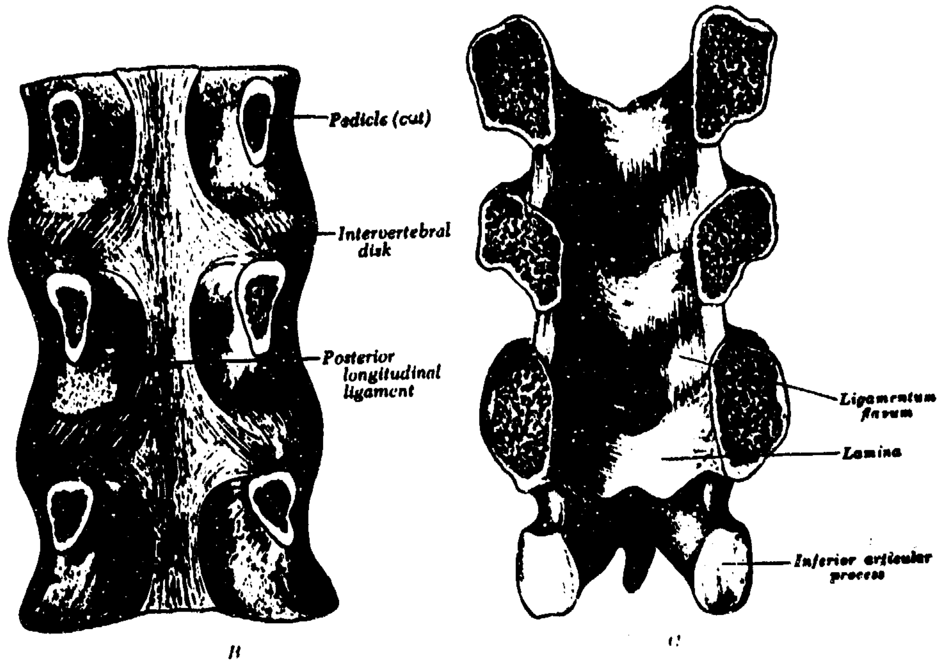


Figure 19. The posterior longitudinal ligament (from Epstein, 307).

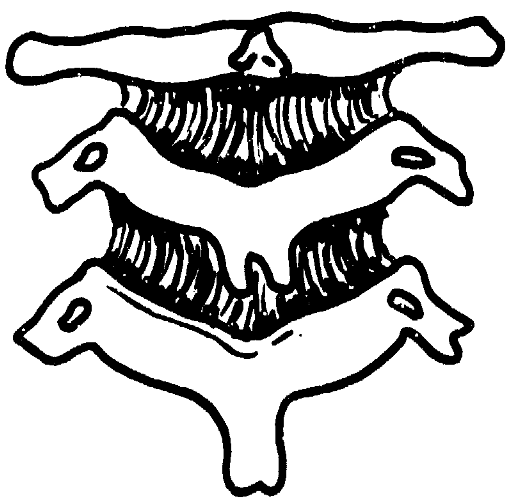
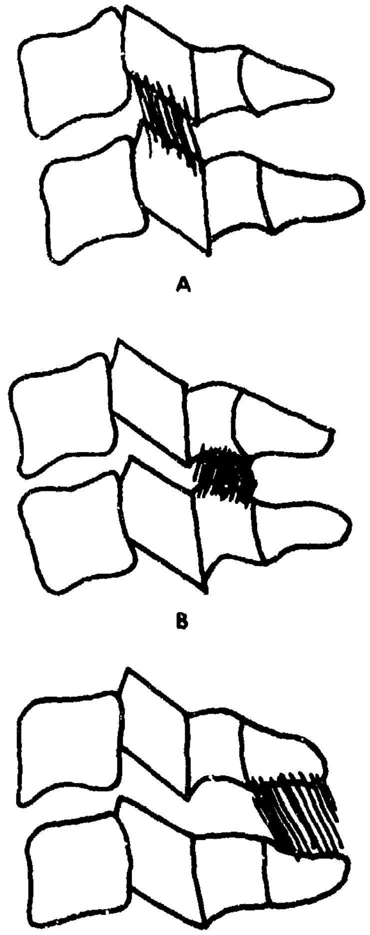


Figure 20. The yellow ligament in the cervical column (after Gerlock).



A

B

C

Figure 21. (after Gerlock)

a) Capsular ligaments

b) Yellow ligaments
(interspinous ligaments)

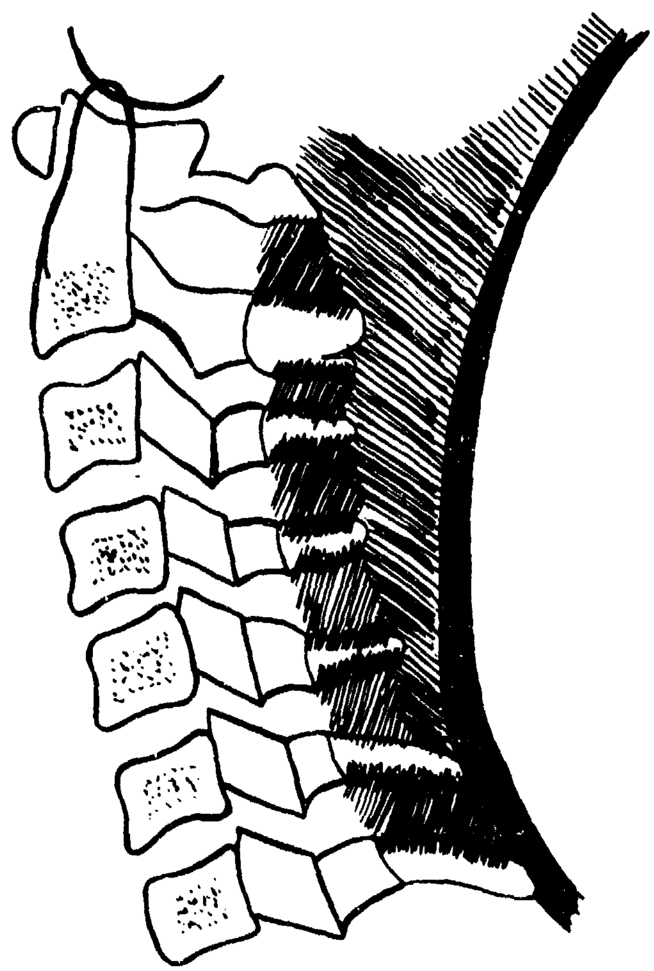


Figure 22. The posterior longitudinal ligament in the neck (after Gerlock).

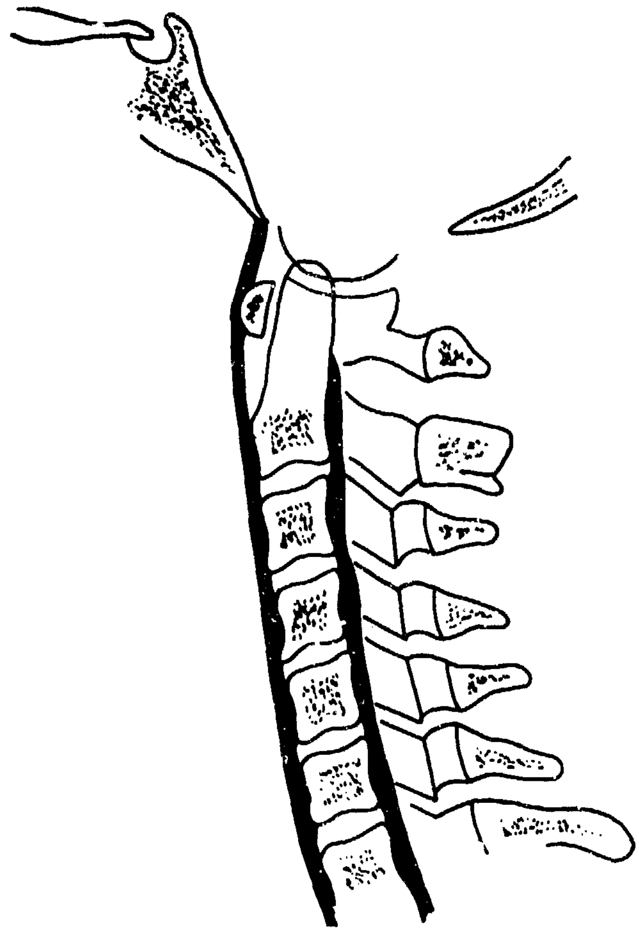


Figure 23. The anterior and posterior longitudinal ligaments in the neck.

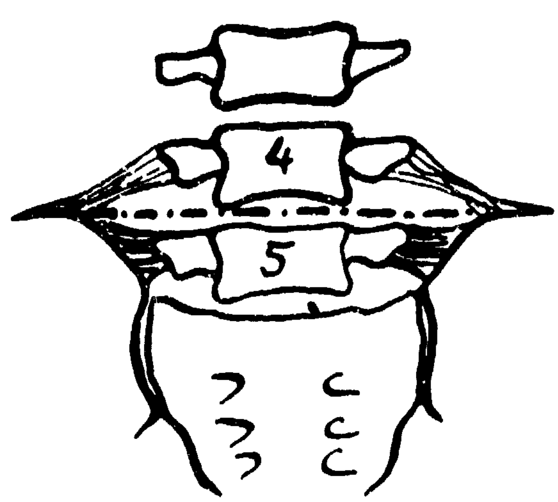


Figure 24. The lumbo-sacral ligaments.

The median atlanto-axial joint lies in the midline. The odontoid process (dens) is retained in an osteo-fibrous ring closed in front by the anterior arch of the atlas and behind by a fibrous band - the transverse ligament. With its upper and lower extensions, the transverse ligament is known as the cruciform ligament. The occipital odontoid ligaments serve to retain the dens within the ring of the atlas.

The atlanto-axial joints lie on both sides. The lower articular surfaces of the lateral masses of the atlas are convex, like those of the axis. Lacking an interarticular meniscus, they are therefore not conformal, and allow rotatory movements of the head. Anterior and posterior atlanto-axial ligaments, together with one atlanto-occipital ligament, strengthen the articulation.

2.4.3.2. The lumbo-sacral joint projects forward. It has little resemblance to those which unite the lumbar vertebrae and has two interesting peculiarities; the articular surface of the body of the first sacral vertebra is inclined at 30° to the horizontal and faces forwards, and the surfaces of the superior articular process of the sacrum face slightly inward and strongly backwards.

As a result, the fifth lumbar vertebra lies astride the first sacral vertebra. Because of the angle of inclination of the latter, the spine would have a tendency to slide forward were it not supported by the inferior articular processes of the fifth lumbar vertebra, which mate with the superior articular surfaces of the first sacral vertebra.

A lumbo-sacral ligament joins each side of the transverse process of L5 to the anterior lateral portion of the wing of the sacrum (Fig. 24).

2.5. THE SPINE AS A WHOLE (Figs. 25, 26, 27)

The average length of the vertebral column is 75 cm, of which one third is made up of the intervertebral discs. The anteroposterior and transverse diameters reach their greatest dimensions at the base of the sacrum, and diminish above and below.

2.5.1. In the sagittal plane the spine describes the following curves from top to bottom. The cervical curvature is convex forward: this is a lordosis. The thoracic curvature is concave forwards: this is a kyphosis, the angle of which can be measured on radiograms, relative to a projection from the upper surface of D4 and the lower surface of D11. It is normally 30-35°. This curvature is structural in origin, because the anterior faces of the vertebrae are shorter than the posterior faces.

The lumbar curvature is lordotic. Its deflection is measured between the posterior upper corner of the body of L1 and the posterior lower corner of that of L5, and the angle of its backward reversal by dropping a perpendicular from the posterosuperior corner of the body of L1. This curvature, like that of the cervical spine, is due mainly to the cupped shape of the intervertebral discs.

The concavity of the sacrococcygeal curvature is directed forwards and, with the lumbar spine, forms a dihedral angle open at the front of which the mean value is about 10°. It is measured by drawing tangents to the lower surface of L5 and the upper surface of S1. It results from the opening of the L5/S1 disc space, which is wider in front than behind, and thinner than the L4/L5 disc immediately above it.

These curvatures differ from one person to another and vary with age. The normal anatomical curves have a mechanical basis; they increase the flexibility and the shock-absorbing capacity of the entire spine, at the same time preserving adequate rigidity and stability at the level of the intervertebral joints (390, 391). When forces are applied to the entire spinal column, the cervical and lumbar lordoses diminish sooner than the thoracic kyphosis.

2.5.2. In the frontal plane, the spine is theoretically straight, but in fact, curvatures are frequently found. They are generally modest without accompanying rotation of the vertebral body, and result in what is known as the scoliotic posture. This is extremely common but has no pathological significance. According to Testut, it is a normal finding at the thoracic level and is concave to the left, corresponding with the path of the aorta.

The anterior surface of the spine thus constitutes a cylindrical column formed by the superposition of the vertebral bodies, the volume and strength of which increase regularly from top to bottom. The posterior surface exhibits the spinal crest formed by the superposition of the spinous processes and, on each side, the vertebral gutter. The lateral aspects show, behind the vertebral bodies, the pedicles and foramina, and the transverse and articular processes. Four zones are shown schematically in Fig. 14.

- the column of vertebral bodies and discs
- the column of pedicles and the spinal canal
- the column of apophyses
- the spinous processes.

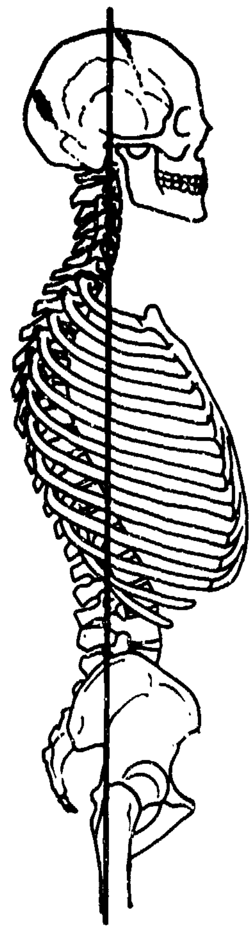


Figure 25. Sagittal geometry of the whole spine, showing the cervical, thoracic and lumbar curves.

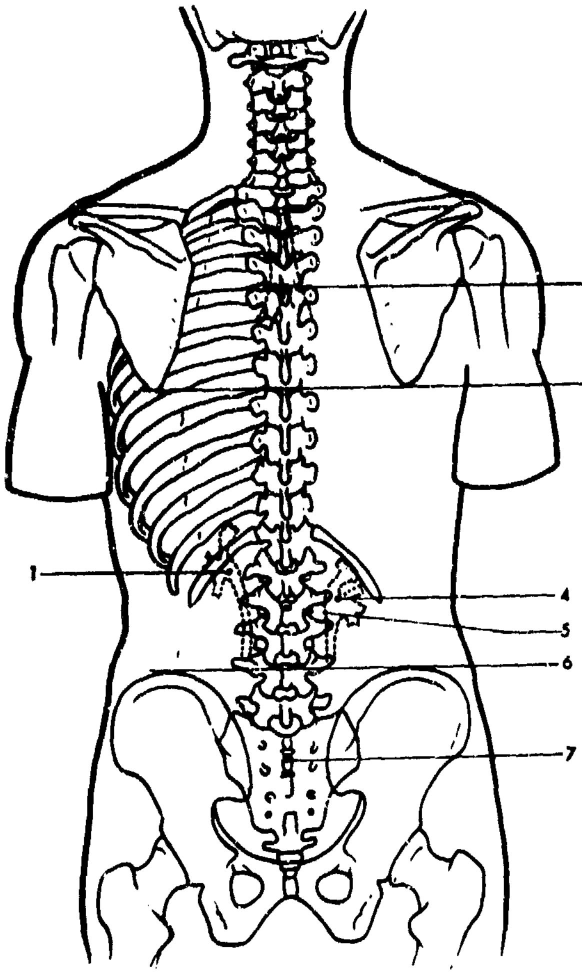
2.6. THE SPINE IN THE SEATED POSITION (52, 53, 57)

"Curvatures of the vertebral column are not primary, but acquired. During the first phase of intrauterine life, the column is essentially straight or describes, in its entirety, a gentle curve concave to the front. At the fifth month, the sacro-vertebral angle begins to appear, establishing the respective limits of the lumbar and sacral regions. But even at birth there exists no trace of the inflections which characterise the cervical and lumbar regions. These inflections do not develop until much later: the first in the third, fourth and fifth months after birth, the second at three to five years" (442).

The lumbar "saddle" is more or less marked, depending upon the individual. It does not exist in quadrupeds or the newborn.

What happens when man changes from the erect posture to a sitting position? The lumbar saddle tends to disappear and the physiological thoracic kyphosis becomes much less evident. The cervical curvature usually remains almost unchanged. Keegan (147) emphasises the important role of the posterior muscles of the thigh and of the buttocks in the disappearance of the lumbar curvature in the sitting position. But if the thighs are flexed upon the trunk, there is a rotation of the pelvis, and the lordosis entirely disappears.

The radiographic studies which we have undertaken, both at the Hospital Dominique Larrey and at the Hospital Begin confirm these changes in the spinal geometry, but the findings are strongly influenced by the state of the spine, by the angle of inclination of the seat, and by the degree to which the subject is forced into it.



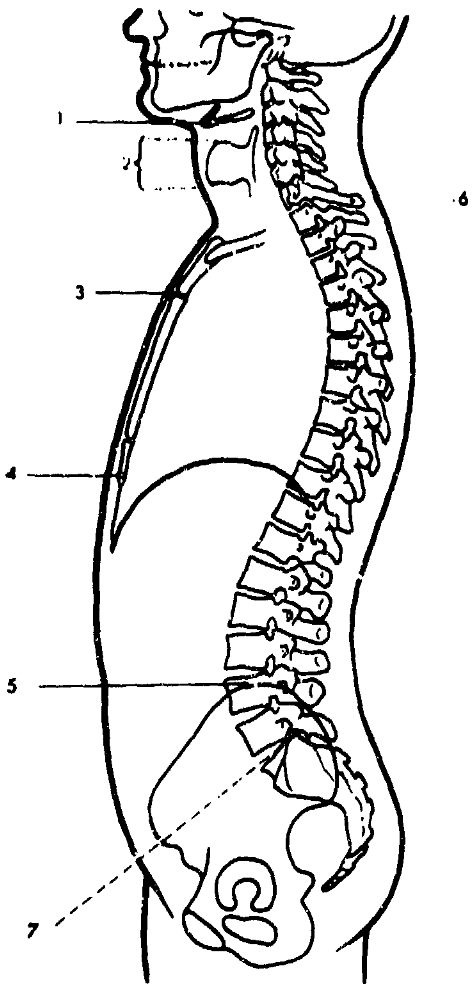


Figure 26. Major spinal references - frontal view

1. Left hemi-diaphragm - body of L1
2. Tracheal bifurcation - D4/D5 disc
3. Point of scapula - D7
4. Right hemi-diaphragm - body of L2
5. Tip of spinal cord - L2
6. Iliac crest - L4
7. End of dural sac - S2

Figure 27. Major spinal references - lateral view

1. Hyoid - C3
2. Thyroid - C4/C5
3. Angle of Louis - D4
4. Xiphoid process - ca D10/D11
5. Iliac crest - L4
6. Most prominent spinous process - C7
7. Bisector of lumbo-sacral disc

Atlas	Tip of mastoid; palatine arch
Axis	Maxilla; alveolar border
C3	Hyoid bone
C4-C5	Thyroid cartilage
C6	Cricord cartilage
C7	Most prominent spinous process
D4	Angle of Louis
D6-D7	Angle of scapula
D8	Nipple line (male)
D9-D11	Xiphoid process
L4	Bi-iliac line. It usually passes a little below the umbilicus, the site of which is too variable to be considered a fixed reference point.
S2	Interspinal line (anterior superior iliac spines)

Table of bony reference points

CHAPTER 3 - BIOMECHANICS OF THE SPINE

C. Kleitz and R.P. Delahaye

SUMMARY

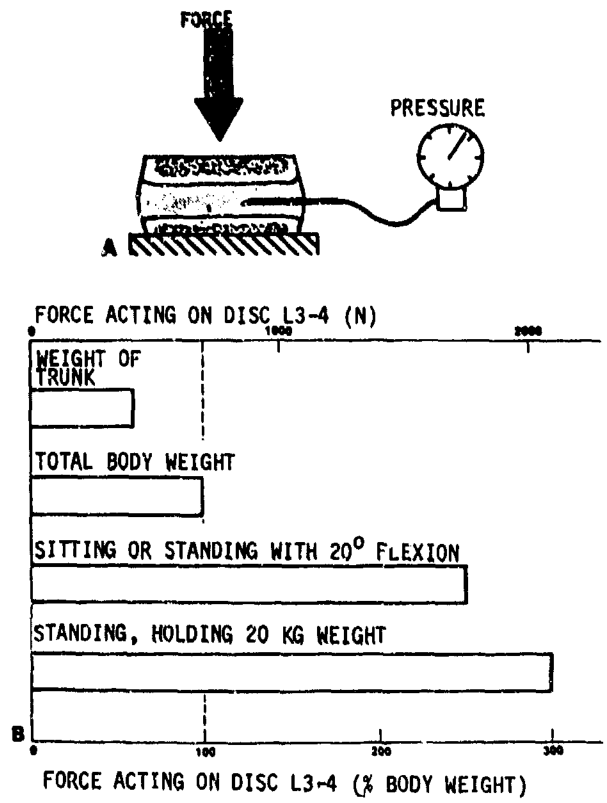


Figure 28. Intradiscal pressure measured by a manometer probe inserted in the nucleus pulposus of a cadaveric functional unit

(from Nachemson)

Measurements from volunteers using the same probe at L3-4, with variations of position and performing a task.

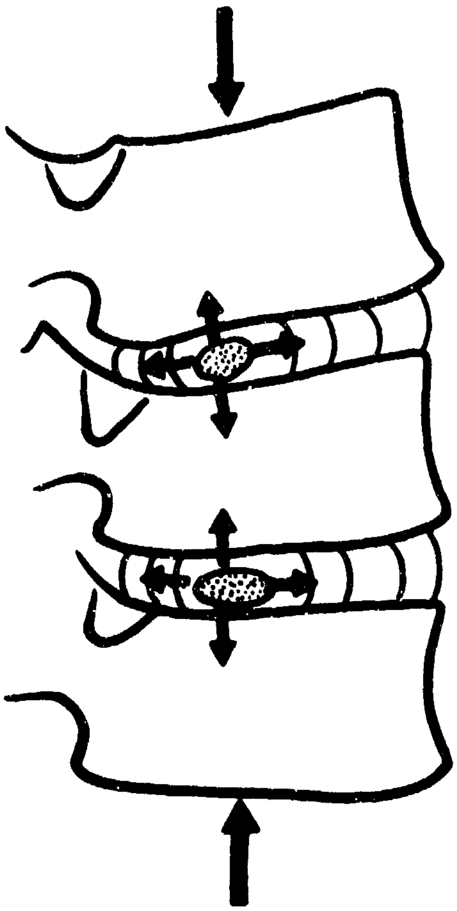


Figure 29. Diagram of the distribution of primary forces on the nucleus pulposus and the deformations of the intervertebral disc.

The vertebral column is a complex mechanical structure in which the vertebrae are connected in a controlled fashion by an assembly of ligaments and of levers. The long, thin structure is given rigidity by the thoracic cage.

The spine has at least three basic biomechanical functions:

- it transmits the weight and the flexing movements of the head and the trunk to the pelvis

- it allows physiological movement between head, trunk and pelvis

- it protects the spinal cord from the trauma caused by forces and movements.

The biodynamics of the spine have been the subject of very many investigations. We must cite, in particular, the well documented study of White and Penjabi (449), which has largely inspired the writing of this chapter.

3.1 BIOMECHANICS OF THE INTERVERTEBRAL DISC (251, 377, 449)

The intervertebral disc, which has numerous functions, is subject to a considerable variety of forces and moments of force.

It sustains all the compressive forces to which the trunk is submitted (334). These stresses become greater as the weight of the body above the disc increases. According to Nachemson (378, 380), the force acting on a lumbar disc in the sitting position is equal to at least three times the weight of the body. Moreover, the slightest activity giving rise to dynamic forces causes an increase in the load upon the disc, which can reach double that sustained in the static position (Fig. 28).

The intervertebral disc is subjected to other types of forces and stresses:

- tensile stresses arise during movements of extension, and of anterior and lateral flexion

- axial rotation of the trunk on the pelvis generates torsional forces which, in their turn, produce shearing stresses in the interior of the disc.

The forces acting on the intervertebral disc are of two types:

- forces of short duration and low amplitude, which can cause irreparable lesions to the disc if they are greater than the failure load at a given point

- forces of low amplitude and long duration, which give rise to disc lesions as a result of fatigue.

The mechanism of the two is different, because the intervertebral disc has some properties which are time variant; fatigue and viscoelasticity (which is characterised by hysteresis); creep and relaxation (449).

3.1.1. Compression Characteristics (Figs. 29-31)

Numerous studies have been conducted on experimental models generally consisting of segments with at least two vertebrae and an intervertebral disc, and theoretical calculations have also been made (349). Compressive forces in a single axis have been considered (267, 312, 334, 335, 406, 407, 445, 309, 310). The curve representing the relationship between the applied force and the deformation produced by the compression has been very useful in explaining the physical behaviour of specimens from widely different experiments. The curve is sigmoid in form. Initially concave to the axis of the force, it becomes rectilinear, then convex shortly before rupture of the disc. This graphical representation indicates that the disc offers little resistance to moderate forces. It retains its flexibility. Then, as the force increases, it becomes more rigid and more stable. In response to very large forces, no herniation of the disc occurs as a result of compression alone, even if a posterior lateral incision has been made in the annulus fibrosus (445, 334, 335, 373). The relative forces on the disc and on the vertebral body were compared by Brown et al (267) using functional units of the lumbar column. The first component to fail in compression was the vertebra, in the form of a fracture of the surfaces. The disc was never ruptured. The mode of fracture depended on the state of the vertebral body (osteoporosis). In osteoporotic vertebrae, the plateaux and the underlying bony tissue are highly compressed in response to relatively weak forces (Fig. 31).

Farfan (312, 313) showed that a degenerate disc is less resistant to compression than a normal disc, which is confirmed by the clinical observation that ruptures and herniations of the disc are more frequent after the age of fifty. Studies made after injecting the disc with contrast medium (discography) show that before fracture of the vertebral plateaux, the nucleus penetrates the vertebral body, creating a hernia in the spongiosa. It must be concluded that the tendency of the disc to suffer the posterolateral hernia so often seen clinically greatly depends on forces other than those of compression (440).

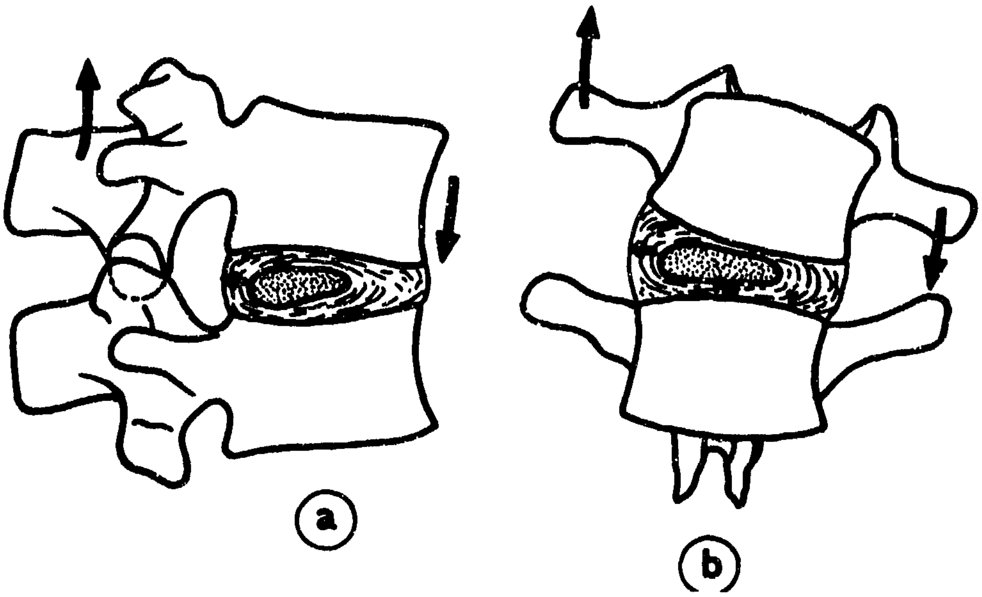


Figure 30. Diagram of displacement and deformation of the nucleus pulposus and fibrous ring during spinal movements (from Paturet).

a) anterior flexion
b) lateral flexion

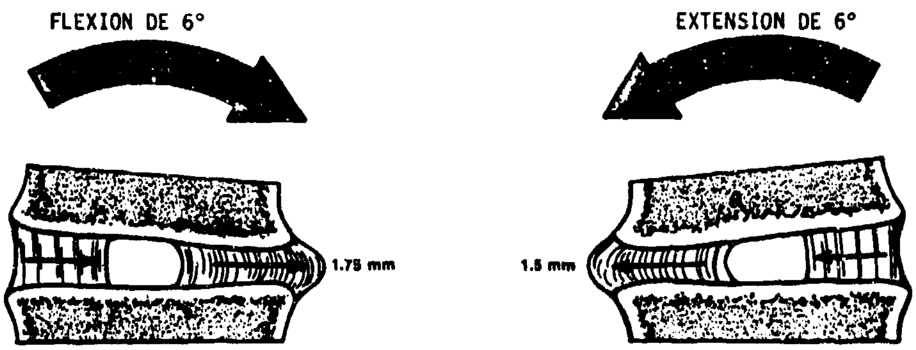


Figure 31. Protrusion of the disc in flexion and extension. Flexion and extension of the vertebral column demand a horizontal movement of the disc. In both cases, there is protrusion of the disc on the concave side, and constriction on the side of the convexity.

3.1.2. Tensile Properties

Forward flexion, extension, and lateral flexion expose the annulus fibrosus to axial tensions. Axial rotation also generates a tensile stress inclined at 45° to the axis of the vertebral column. Compression also causes stresses through tension. Thus, the disc is subjected to tensile forces in all directions. From curves of tensile strength derived by Brown (267) it is apparent that the anterior and posterior regions are generally more resistant than the lateral and central areas (nucleus pulposus). In directions other than axial (321), the disc is three times stronger in the direction of the fibres of the annulus than in the horizontal direction.

3.1.3. Flexion Characteristics

The forces applied in flexion and in torsion are even more traumatic to the disc than forces of compression, as shown by several experimental studies (312).

The slightest physiological movement in flexion causes the anterior part of the disc to protrude. In extension, the posterior part is affected, and in lateral flexion the disc bulges on the concave side of the curvature and is compressed on the convex side (sic) (267). Roaf (406) has shown that these movements cause no change in the shape or position of the nucleus pulposus.

3.1.4. Response to Torsion

Farfan (311) considers that torsion may be the principal cause of spinal trauma. Experimentally, he has made continuous recordings of the deformation of the disc in a functional vertebral unit (including the posterior elements) subjected to torsion about a fixed axis passing through the posterior part of the disc. The curves obtained have a sigmoid shape. To produce rupture of the disc, an average rotation of 16° was found to be necessary for normal discs. For degenerate discs the angle was less than 14.5° under the experimental conditions used.

3.1.5. Resistance to Shear

With torsional stresses, the disc is subjected to shearing forces which are not uniformly distributed. They are larger in the periphery and weak at the centre. Experiments on shear in the horizontal axis (antero-posterior direction) have been carried out on lumbar discs. A large force is required to produce lesions; its value is of the order of 260 Newtons (373) and is of clinical importance. In fact, a very large force is needed to produce abnormal horizontal displacement of a normal disc. The annulus is rarely damaged by shear alone, and it is quite certain that clinical cases of rupture of the annulus result from combinations of flexion, torsion and tension.

3.1.6. Creep and Relaxation

Creep is the deformation of the disc associated with the sustained application of a load. Kazarian (344) carried out tests on segments of the spinal column, and classified the discs into four categories according to the extent of their degeneration (Fig. 32).

The overall deformation of a normal disc is smaller, and appears more slowly, than that of a degenerate disc. Thus, degeneration reduces the viscous elasticity of the disc. In other words, the degenerating disc becomes less and less able to cushion impact and to distribute uniformly forces applied to the whole vertebral surface.

It should be noted that no acceptable experimental model exists for representing the clinical problem of degeneration of the disc.

3.1.7. Hysteresis (Fig. 33)

Hysteresis is a phenomenon consisting of loss of energy when a structure is submitted to repetitive cycles of compression and of decompression. In biological tissues, hysteresis is an expression of the irreversibility of mechanical behaviour, and it may be more or less pronounced. Virgin (445) was the first to demonstrate this protective mechanism in the discs. Hysteresis increases with the applied force. It is higher in the lower lumbar region, and diminishes with age.

Hysteresis decreases if the force is applied for a second time, which indicates that the body is poorly protected against repetitive stresses (Fig. 33).

3.1.8. Resistance to Fatigue

The disc has a low capacity for restoration and regeneration. Few documented studies are reported in the literature. Brown (267) showed experimentally that the resistance of the disc to fatigue is low. Its tolerance *in vivo* remains difficult to determine. Fig. 34, taken from the paper of Hartung and Anna (332), is a theoretical representation of the fatigue induced by continuous loading and unloading. It appears that the maximum force that can be tolerated decreases in proportion to the number of cycles. As the threshold line for lesions crosses into the physiological zone for a given structure, the danger of rupture (for a disc) or of fracture (for a bone) becomes greater and greater.

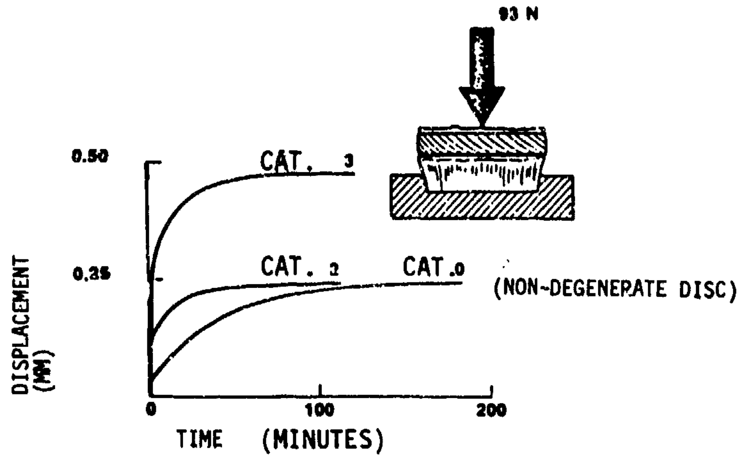


Figure 32. Creepage of disc (after Kazarian, 344).

The non-degenerate disc (category 0) deforms less rapidly and more easily than the degenerate disce (category 3).

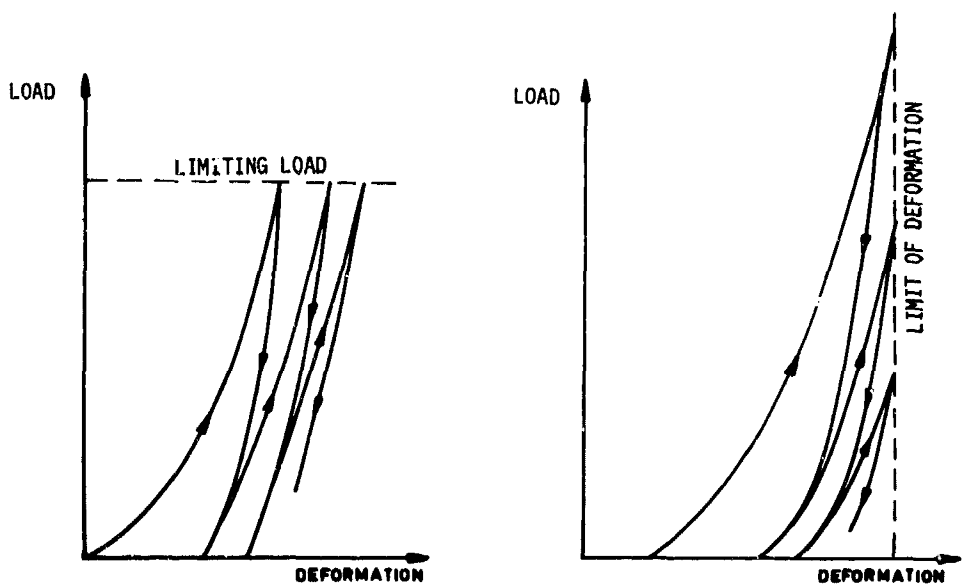


Figure 33. Hysteresis curves of biological tissues limited by load and by deformation (after Hartung and Anna, 332).

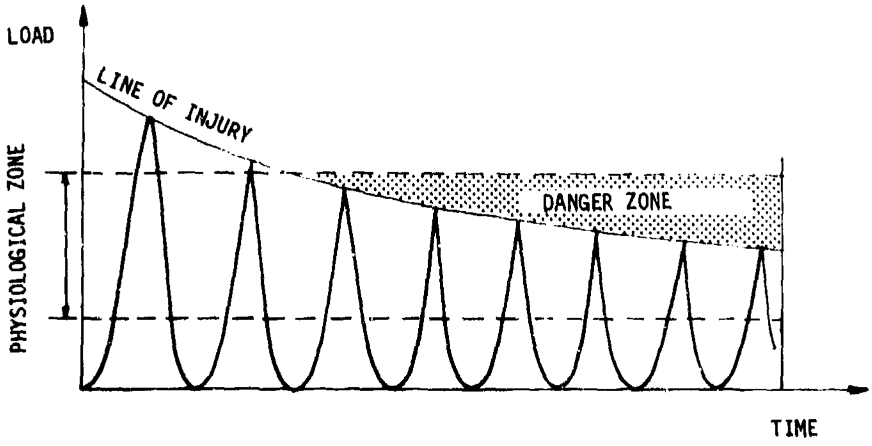


Figure 34. Assessment of strength as a function of time with loading and unloading to the deformation limit; the maximum load decreases (after Hartung and Anna, 332).

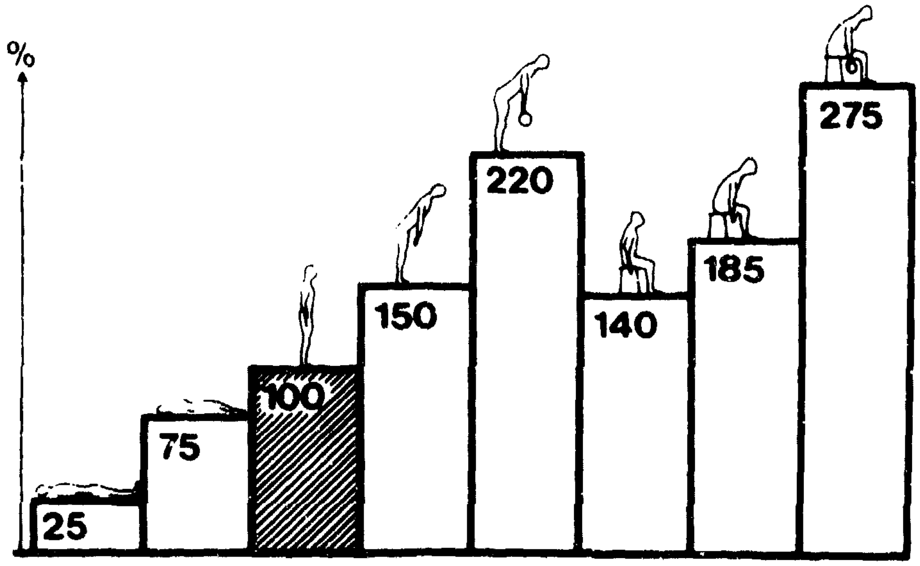


Figure 35 a. Disc pressure *in vivo* (L3) during effort and in various postures. The pressure is higher in the sitting position than when standing.
(from Nachemson, 383)

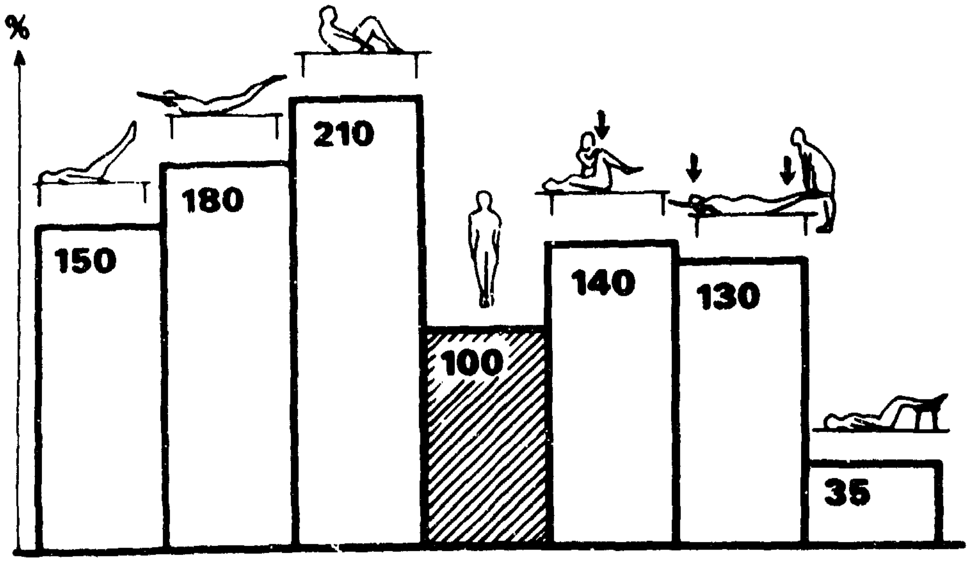


Figure 35b. From Nachemson; changes in the recumbent posture.

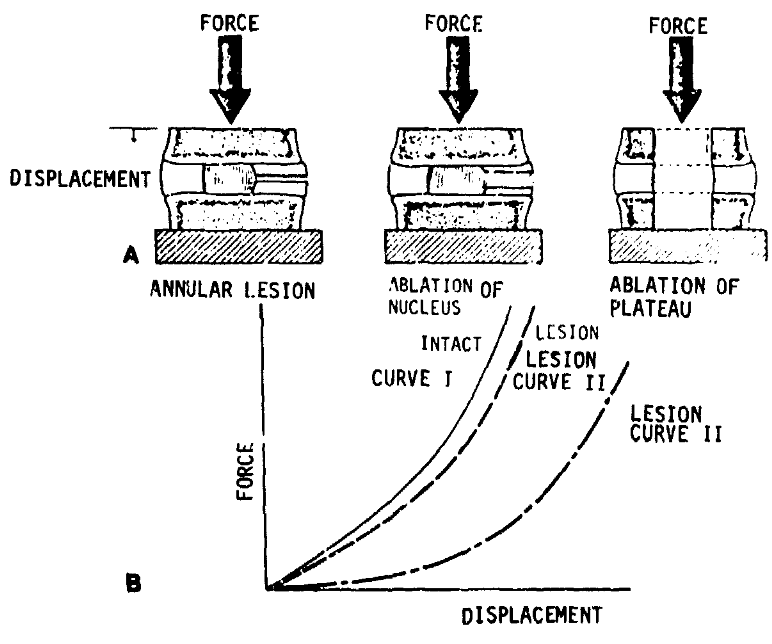


Figure 36. Biomechanical behaviour of a damaged disc.
Based on 3 forms of injury: annular lesion caused by breach of the posterolateral wall of the annulus, with a hold 3-4 mm in diameter; total ablation of the nucleus through a tunnel in the annulus; ablation of the vertebral end-plates by extrusion of the nucleus.

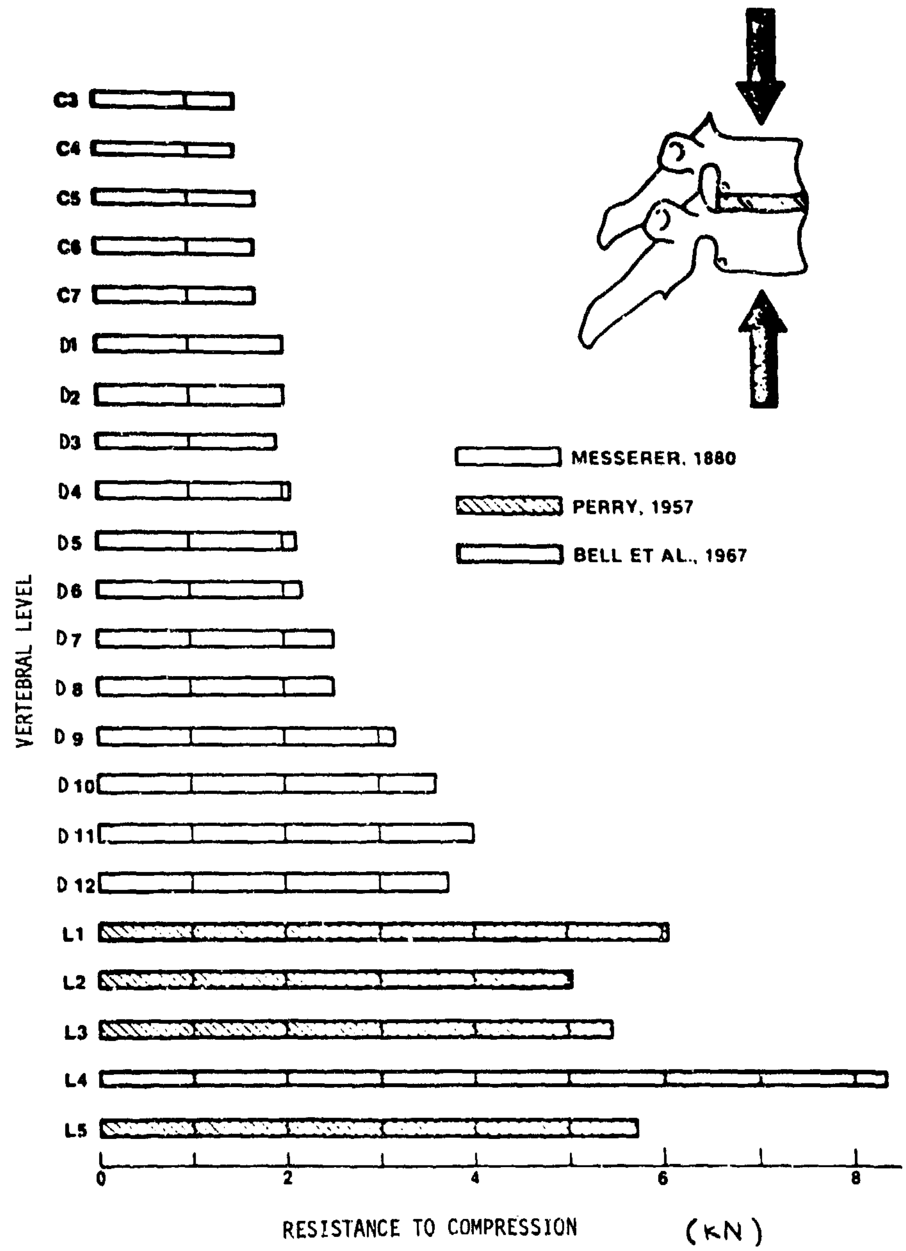


Figure 37. Resistance to compression (KN) (from White III and Panjabi, 449).

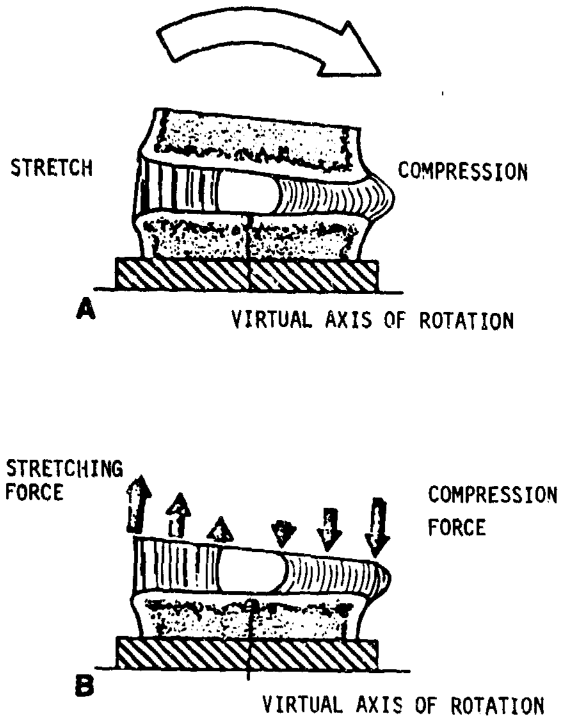


Figure 38. Constraints produced by flexion (after White III and Panjabi, 449).

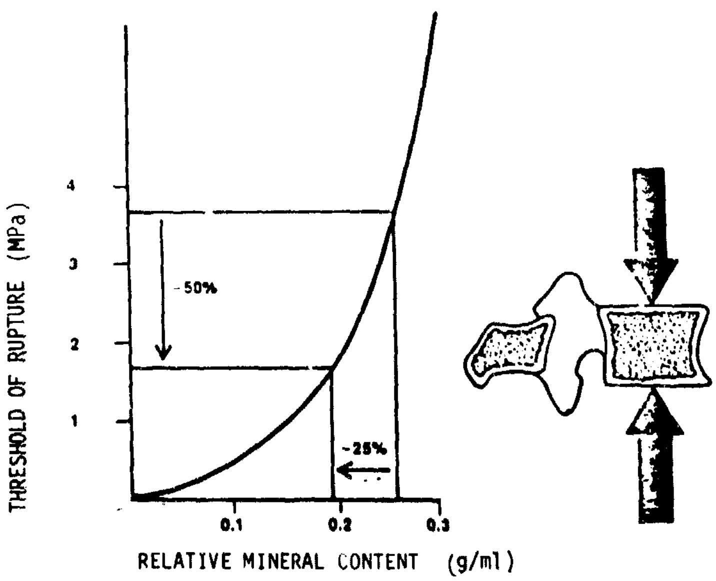


Figure 39. Relationship between bony tissue and vertebral strength.

3.1.9. Pressure in the Disc

It is difficult to determine the magnitude of the forces applied to a disc. Nachemson et al (378, 379, 380) estimated them *in vivo* , using the principle that the nucleus is a force sensor. They showed that the pressure in the liquid medium inside a nucleus was directly related to the axial pressure applied to the disc. Pre-stressing of the discs was demonstrated, in volunteer subjects, by measuring the pressure in the disc between L3 and L4 using a special needle fitted to an electromanometer. The disc sustains quite a large force, estimated at 120 Newtons, despite the fact that the disc L3/L4 supports no more than 60 per cent of the body. In the sitting posture, or standing with 20° of flexion, this force reaches 200 per cent of the body weight, while if the standing subject holds a weight of 20 kg in his hands, the force approaches 300 per cent of the body weight (Fig. 35).

3.1.10. Autofiltration (Fig. 36)

The disc is not directly vascularised, and it is probable that a special mechanism of restoration comes into action: autofiltration. Markoff (373) and Morris (377) demonstrated experimentally that there exists a very singular phenomenon of adaptation which does not depend upon the viscocity or the elasticity of the disc, but it must be noted that these experiments used a single type of force; compression. Moreover, is this immediate restoration definitive, or is it modified in time?

3.1.11. Functional Biomechanics of the Disc

The conclusions drawn from analyses reported in this chapter rest upon experimental observations, but the forces applied in life are extremely complex.

1. Compression (Fig. 37)

In the young subject, the nucleus is sufficiently hydrated to behave as a gelatinous mass. When force is applied, the pressure developed in the interior of the nucleus displaces the surrounding structures further from the centre. The vertebral end plates tend to separate one from the other, while the annulus is pushed towards the periphery. The arrangement of the fibres allows the annulus to absorb the stress.

If the nucleus is dry it is unable to produce a sufficiently high hydraulic pressure. The forces are then distributed more over the peripheral regions.

2. Tension

Because of the development of shearing forces, the risk of rupture is greater in tension than in compression. The dimensions of the disc are also affected differently; it bulges in compression but is compressed in tension.

3. Flexion (Fig. 38)

One part of the disc is subjected to pressure while the other sustains tension, each type of force being applied to one half of the disc. The net force on the disc is a combination of the two. The side of the annulus under tension contracts, while the side in compression expands.

4. Torsion

This produces horizontal and axial shearing forces, the magnitude of which varies proportionally to the distance between the point of application of the force and the axis of rotation. The annular fibres which are arranged obliquely with respect to the horizontal plane are able to resist these stresses.

5. Shear

Shear acts in the horizontal plane perpendicular to the axis of the spine.

These analyses show how various combinations of functional forces can sometimes create enormous stresses in the interior of the disc. Rupture undoubtedly results from the action of a combination of these forces.

3.2. BIOMECHANICS OF THE INTERVERTEBRAL LIGAMENTS

The ligaments are linear structures which oppose the action of forces applied in the axis of their fibres. They are strongly resistant to tensile forces. These ligaments act when the functional unit (vertebra - disc - vertebra) is subjected to various complex force vectors and couples.

The ligaments, while allowing physiological movements, maintain the vertebrae in a fixed position with respect to each other. They contribute to the protection of the spinal cord against trauma.

3.2.1. The Anterior and Posterior Longitudinal Ligaments

These are attached both to the intervertebral disc and to vertebral body. They deform as a result of relative separation between two adjacent vertebrae and also when the intervertebral disc bulges. According to Roaf (406, 407) it is not possible to rupture the anterior longitudinal ligament by flexion or extension, although it is possible to do so by rotation. Like the discs, these ligaments degenerate with age, with a loss of their damping properties. The anterior ligament is twice as strong as the posterior one.

3.2.2. The Yellow Ligament

Nachemson and Evans (381) note that the yellow ligament is in a state of pretension when the vertebral column is in a neutral position. These resting forces diminish with age. Of all the tissues in the body, the yellow ligament contains the highest percentage of elastic fibres. This characteristic allows it to undergo considerable elongation.

3.2.3. Interspinous and Supraspinous Ligaments

The torsion of these ligaments increases in proportion to the flexion of the column. Few studies of them have been made.

3.2.4. Rupture of Ligaments - Disruption of Bones

The ligaments transmit tensile forces from one bone to another. Large forces can give rise to disruption of the ligament, of the bone, or of the point of attachment. The site of the lesion depends on numerous factors. According to Noyes et al (387) fractures are produced by low impact velocities, and ligaments are torn at high speeds. It can be concluded that the strength of the bone increases relatively more than that of the ligament as the speed of application of force increases. Immobilisation reduces the strength of bone more than that of ligament.

3.2.5. Functional Biomechanics of the Ligaments

The anterior and posterior ligaments, as well as the yellow ligament, possess similar biomechanical characteristics. According to the work of Nachemson and Evans (381), the yellow ligament, which is situated behind the rotational axes of flexion and extension, contracts during extension of the column and stretches during flexion (443). Calculations show that in total extension it shortens by 10 per cent, and that it does not encroach upon the spinal canal in response to extension. In total flexion, it extends by 35 per cent; this is the physiological range. A secondary elongation of 20 per cent associated with even greater flexion can lead to rupture. Mathematical models (324) have been developed in attempts to understand the role played by the ligaments and the muscles in the biodynamics of the spine.

3.3. BIOMECHANICS OF THE VERTEBRA

The first biodynamical study of the spine in man measured the strength of vertebrae (Messerer, 1880) and, since then, many research workers have tried to define the mechanical properties of human vertebrae and to understand the respective role of the ligaments, the muscles and the bones (364, 366, 368, 393, 400, 417, 430).

The shape and position of the posterior articular facets influence the extent of the movements described by the spine.

3.3.1. The Vertebral Body

Determination of the resistance of the vertebral body to compressive forces has involved numerous studies, which have been stimulated for the most part by the frequency and severity of fractures of the spine.

Factors in the Variation of Vertebral Strength

1. Level of the Vertebra

Here, the size and the morphology of the vertebra play their part.

2. Age

Bell et al (449) have shown that there is a good relationship between the strength and the mineral content of osseous tissues. Thus, the loss of 25 per cent of mineral reduces the vertebral strength by more than 50 per cent (Fig. 39). This property is related to the architecture of the trabeculae in the vertebral body.

3. Topographical and Tissue Factors

The vertebral body bears the greater part of compressive forces acting upon the spine. This force is transmitted from the upper to the lower surface through two media; the cortical shell and the spongy "kernel" (cancellous zone). Rockoff et al showed experimentally that, up to the age of 40 years, 55 per cent of the force was borne by the cancellous zone and only 45 per cent by the outer shell. After the age of 40, the cancellous zone supported only 35 per cent and the shell 65 per cent (Fig. 40). In response to compression this cribriform zone undergoes large deformations, which reach 9.5 per cent before fracture occurs. The deformation produced in cortical bone by an identical force is less than 2 per cent.

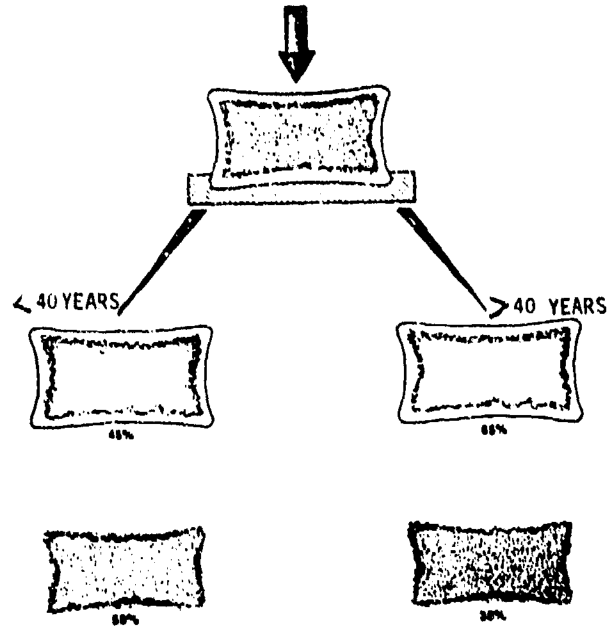


Figure 40. Relative strength of the two components of the vertebral body: the cortical shell and the spongiosa (after Rockloff and Bleustein, 408).

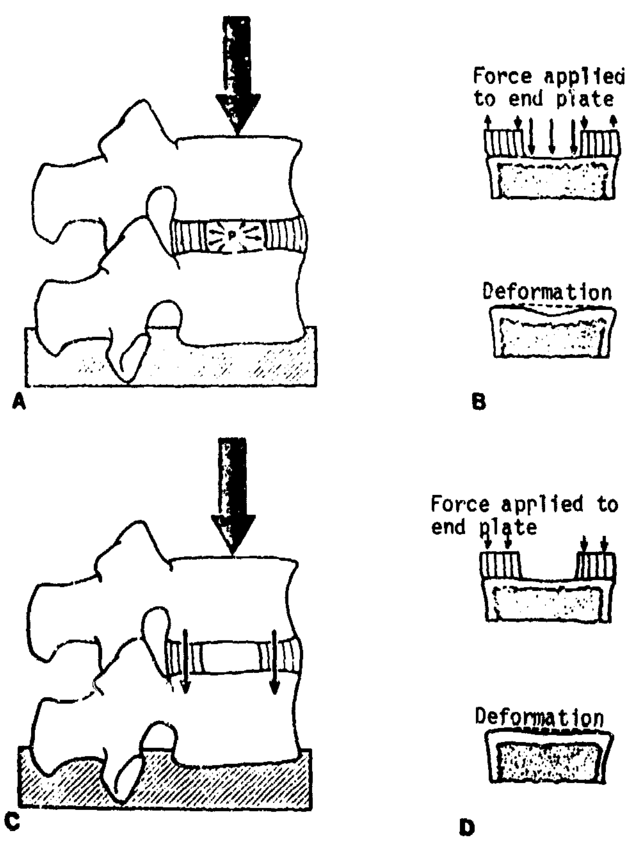


Figure 41. Mechanism of rupture of vertebral end-plate (after White III and Panjabi, 449).

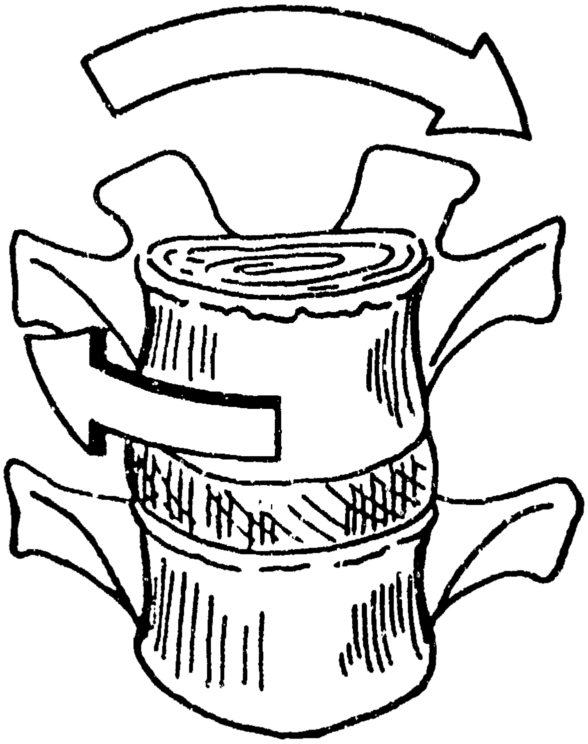


Figure 42. Diagram of form of coupling in the lumbar column (Krag, cited in 449).

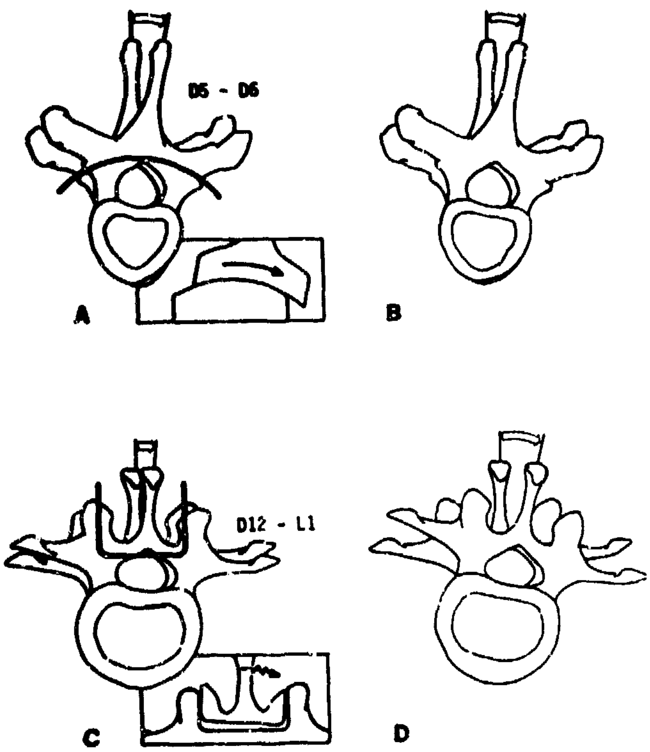


Figure 43. The role of the articular facets (from White III and Panjabi, 449).

a) Axial rotation of one element of the D5-D6 unit with respect to the other is not impeded by the articular facet, because of the orientation of the plane of the facets to the virtual axis of rotation. A fixed axial rotation is produced by a given force.

b) Elimination of the facets does not significantly alter the resistance to axial rotation of D5-D6. Almost the same rotation is produced by the same applied force.

c) The situation is very different for a functional unit in which the orientation causes the 2 facets to engage together when axial torsion is applied. One example of such a unit is D12-L1, which seems to be more resistant to rotation than any other for the same force as in a). Rotation is therefore less.

d) Elimination of the facets at the D12-L1 junction frees the lock, and significantly changes the resistance to axial rotation. Rotation is then much greater for the same force as in a).

Role of the Bone Marrow

Lindhall (365), and later Hayes and Carter (333), showed that the shock-absorbing properties of the trabecular bone are reinforced by the presence of bone marrow, especially in high speed impacts. The marrow thus acts as an hydraulic cushion and, at high impact velocities, the spongiosa supplies the principal component of the strength.

Fracture of the Vertebral Plateaux (Fig. 41)

In 1957, Perry (395, 396) explained the occurrence of fracture of the vertebral plateau as a result of compression. Compression of a non-degenerate disc produces an increase in the pressure in the interior of the nucleus, and also causes compression of the centre of the plateau. This applied force results in deformation followed by a central fracture and herniation into the spongiosa. In a degenerate disc, the non-gelatinous nucleus is incapable of generating a high hydraulic pressure. The compressive force is mainly transmitted from one surface to the other through the annulus. The end plate sustains a large force at its periphery. The stresses are distributed evenly over its circumference, and a fracture of the vertebral body occurs.

3.3.2. The Neural Arch (315, 334, 383, 449)

Experimentally, the neural arch has always been considered as an individual unit. Its strength does not vary with the state of the disc but it always decreases as a function of age.

Nachemson (383) has concluded from his measurements of intradiscal pressure (and from the forces exerted upon the disc) that the articular facets experience about 18 per cent of the total compressive force applied to a functional unit. King et al (449) carried out dynamic studies on whole cadavers. They concluded that the distribution of stresses between the facets and the disc is quite complex. According to the position of the vertebral column, the facets can receive from 33 per cent to 0 per cent of the total applied force.

White (449) and Hirsch (334) have shown that the articular facets and the posterior ligaments limit the physiological movements of the spine. Thus, the posterior mass plays a role in stabilising the vertebral column, particularly if the disc has already ruptured.

3.3.3. Functional Biomechanics of the Vertebra

As Perry (395) and Bell (449) have observed, increasing age leads to loss of strength in the vertebral column, and this is much greater than would be predicted from the osteoporosis. This could be due to the rarefaction of the horizontal trabeculae at the centre of the vertebrae before the age of 50, which seriously reduces the strength, particularly in the middle of the vertebra. This theory is in good accord with clinical observations of collapse of the centre of the vertebral body in patients suffering from osteoporosis.

3.4. BIOMECHANICS OF THE SPINAL COLUMN (346, 377, 449)

Functionally, a vertebral unit is the smallest segment of the column which has biomechanical characteristics analogous with those of the entire spine. The overall behaviour of the column is thus the result of the behaviour of these individual units. Mathematical models allow a relationship to be established between the fundamental physical properties of the individual components of a structure and the structure itself, but the biological interpretation becomes more difficult when the model comprises multiple functional units.

Rigidity is the property which permits a substance to resist an applied force. The coefficient of rigidity is the relationship between the applied force and the displacement that it produces.

Elasticity is the capacity of a structure to deform under the application of a force. The coefficient of elasticity, therefore, is the relationship between the displacement produced and the applied force. It is the inverse of the coefficient of rigidity.

The vast majority of studies of vertebral stiffness have been carried out in compression. The experiments have shown that the functional units of the thoracic and lumbar regions are more rigid in compression than in extension. As the studies of Hirsch, Nachemson (381, 384) and Rolander (409) have shown, the column becomes stiffer in response to large forces.

In the lumbar region the resistance to shear appears to be the same in all directions, anteroposterior and lateral.

In flexion, the column seems to be more flexible (or less rigid) than in extension. The posterior elements act to resist extension. These characteristics do not change with the anatomical level (410).

Axial rotation is certainly the most dangerous movement for the disc. Resistance to torsion is more or less constant throughout the whole of the thoracic region, and increases at lumbar level. Removal of the posterior structures increases the freedom of rotation. According to Gregersen and Lucas (325) the average cumulative rotation *in vivo* is 102^{o} between the first thoracic vertebra and the sacrum.

In practice, physiological movements are closely linked by the coupling phenomenon resulting from the geometry of the vertebrae, the ligaments, and the curvature of the vertebral column (Fig. 42).

This coupling has been the subject of many experiments. It is more common at cervical and lumbar levels than at the thoracic level. Two or more movements are said to produce a couple when it is not

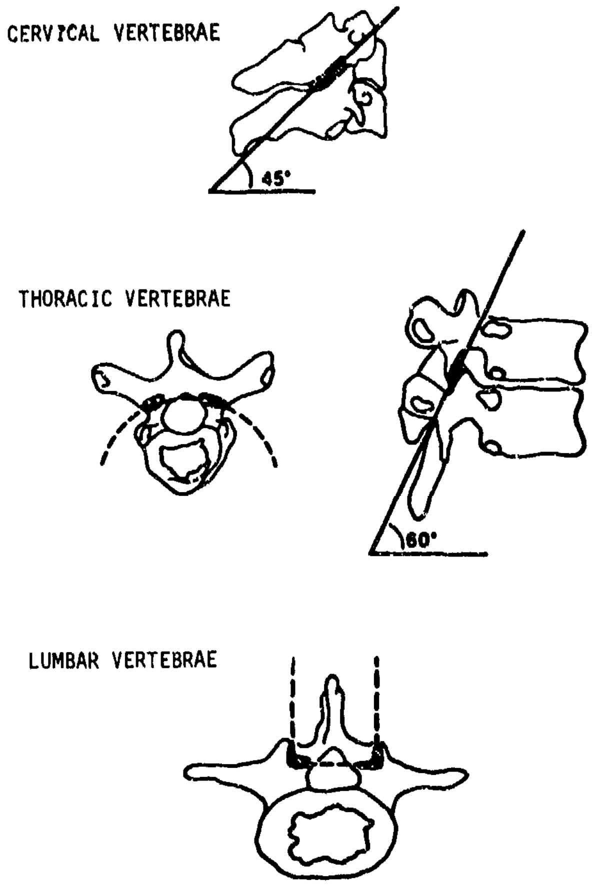


Figure 44. Characteristic orientation of the articular facets in the cervical, thoracic and lumbar regions (from 449).

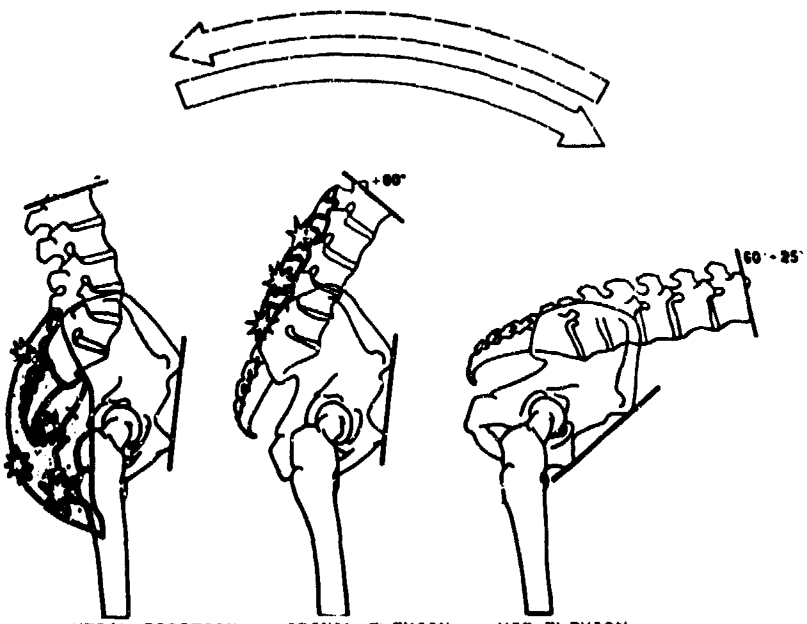


Figure 45. Muscle activity in bending forwards. This is a movement in two phases, involving both the spine and the pelvis (from 449).

possible to produce one without inducing the other at the same time (for example, lateral flexion and rotation). In the thoracic region there is strong coupling between movements in the sagittal plane (translation and rotation). The coupling between axial rotation and lateral flexion is stronger in the lumbar region (449).

The spine is subjected to physiological pre-stresses which are particularly related to the position of the body. At the level of L3/L4, for example, they amount to twice the body weight in an upright individual. The pre-stressing has a strong influence on some indices of strength. The actual properties of rigidity and of elasticity in the vertebral column must be measured in the presence of appropriate pre-stresses, chosen to simulate the conditions that exist *in vivo* . *In situ* , physiological pre-stress is exhibited as axial pressure related to body weight and as flexion. The flexional pre-stresses are counter balanced by the posterior ligaments and muscles.

Role of the Articular Facets (315, 346, 449)

Torsional resistance is largely determined by the shape of the articular facets. If their plane permits almost free rotation (for example, D5/D6) the functional unit has little resistance to rotational force, and only the ligaments limit flexibility. In contrast, the D12/L1 unit has facets which actually limit axial rotation. Accordingly these facets considerably increase the rigidity. It is in fact at the level of the thoraco-lumbar junction that fractures most often occur. The abnormally high rigidity of this structure is a result of the peculiar orientation of the articular facets (Figs. 43, 44).

3.5. THE ROLE OF THE THORACIC CAGE AND THE MUSCLES

The thoracic cage stiffens and reinforces the vertebral column. The costovertebral articulation provides supplementary ligaments which contribute to the vertebral rigidity, and the moment of inertia of the thorax increases the capacity of the thoracic spine to absorb energy.

Even when the ligaments are intact, a vertebral column stripped of muscles becomes an extremely unstable structure. The muscles serve to stabilise the trunk and to carry out physiological movement. They are divided into posterior and lateral vertebral groups, and the prevertebral muscles which are, in fact, abdominal muscles. Morris et al (377) have pointed out that the dorsal muscles are in constant activity in the erect subject.

Anterior flexion takes place in two stages. In the first (on average 60^{o}) the flexion is produced by the lumbar functional units, while the second (25^{o}) results from movement at the hip joints. The tendency to flexion caused by the weight of the trunk is compensated, proportionately, by corresponding increases in the activity of the spinal muscles and the superficial muscles of the back. The muscles relax when hyperflexion is achieved (Fig. 45).

In extension, the activity of the back muscles is increased, while in lateral flexion muscular activity is relatively stronger in the anterior lateral part of the lumbar region and in the homolateral part of the thoracic region. Axial rotation is carried out by the spinal muscles and rotators, and the abdominal muscles are much less active.

Thus, it is clear that the spine can be flexible or stiff, and can support extremely heavy loads. Flexibility and intrinsic stability are ensured by the intervertebral discs and the intervertebral ligaments, while the trunk and the back muscles ensure extrinisic stability.

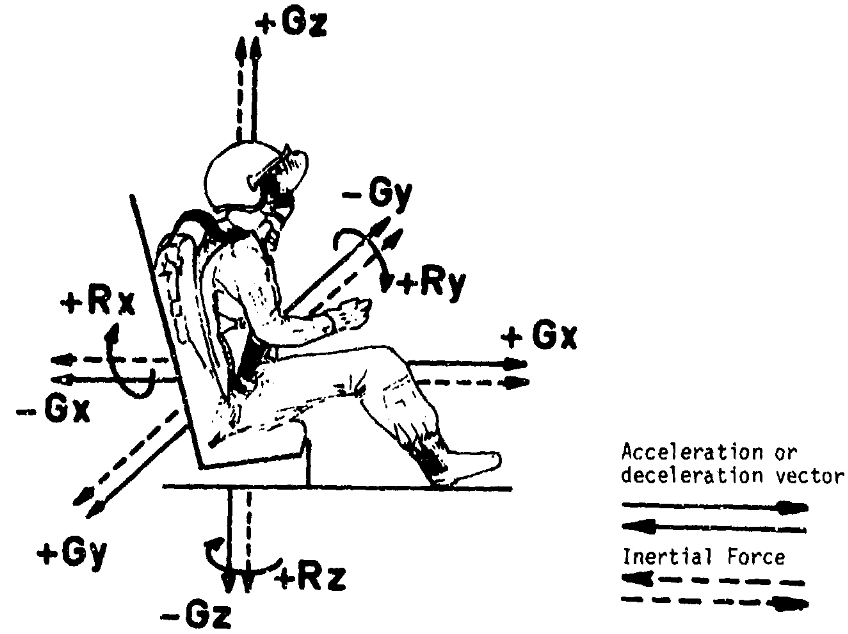


Figure 46. Classification of accelerations with respect to the axes of the body

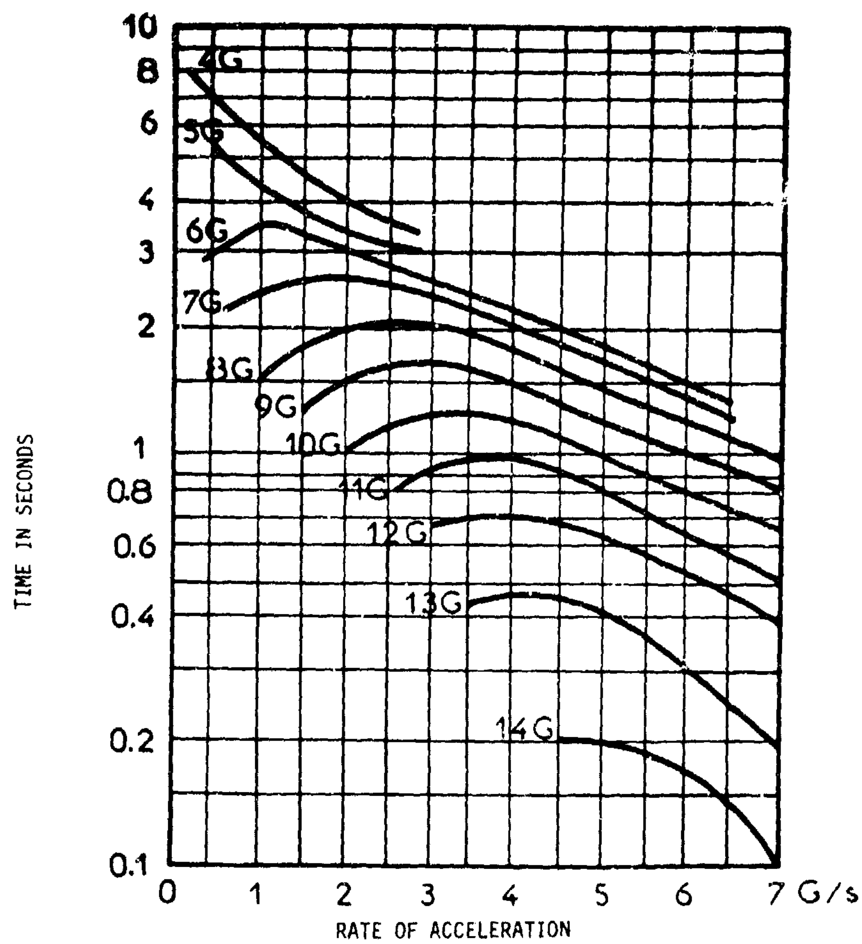


Figure 47. Tolerance time as a function of the number of jolts, for different values of +Gz acceleration.

CHAPTER 4 - SPINAL STRESSES IN FLIGHT

R. Auffret and H. Viellefond

SUMMARY

There are multiple stresses in flight, and they can be divided into two categories:

- "normal" and inherent factors; these consist of vibration and accelerations of long duration.

- accidental factors such as ejection or crash, which expose the skeleton of the pilot to considerable forces applied for a very short time.

4.1. INHERENT FACTORS OF FLIGHT

4.1.1. Accelerations

Modern aircraft, and fighter aircraft in particular, are notable for their manoeuvrability and their speed.

While it remains constant in magnitude and in direction, speed alone has no physiopathological effect on the human body. On the other hand, aircraft manoeuvrability implies sudden changes in the velocity vector, both in amplitude and in direction. These changes are called accelerations. In mathematical terms, acceleration is the time derivative of speed, and it is accordingly expressed in metres per second per second (m/sec^2). In practice, units of G are invariably used - 1 G being the value of the acceleration of gravity in Paris; namely, 9.8097 m/sec^2.

On the basis of the above, it is possible to distinguish between:

- linear accelerations, defined as change only in the modulus of the velocity vector; these arise during take-off and landing

- radial accelerations, defined as change only in the direction of the speed velocity; these are produced in turns

- angular accelerations, where changes occur simultaneously in the magnitude and the direction of the velocity vector. These are very common in spins, in flight through turbulence, during aerobatic manoeuvres, and when control of the aircraft is lost.

Very often, accelerations result from the simultaneous application of several forces to a moving body. These are called composite accelerations. They occur, for example, during ejection, where the acceleration provided by the seat gun is compounded with rotation of the seat and with aerodynamic braking.

This is also the case with the so called Coriolis accelerations, which result from the combination of linear and angular accelerations. They have no effect on the spine, but they generate sensory illusions which can be the cause of loss of control of the aircraft.

In considering the physiopathological effects of acceleration and, in consequence, human tolerance of them, three physical factors must be taken into account:

- the axis in which the forces are applied

- the magnitude of the accelerations

- the time for which the accelerations are applied and their rate of onset or suddenness.

From the physiological standpoint it is the inertial forces which must be considered because they are responsible for the effects. They are equal to the forces generated by the acceleration of the aircraft but act in the opposite sense. They are referred to a system of axes based on the pilot seated in his aircraft (Fig. 46).

Table 4.1 shows the relationship between the axes of the aircraft and pilot, and the direction of application of inertial forces, according to the classification adopted by AGARD.

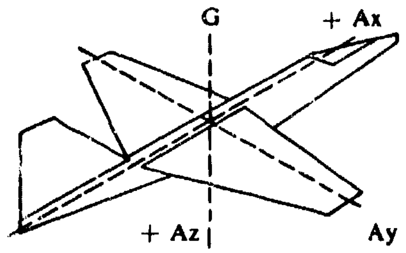


TABLE 4.1

Aircraft Acceleration		Physiological Acceleration	Inertial Force
Forwards	+Ax	+Gx	Backwards
Backwards	-Ax	-Gx	Forwards
Upwards	-Az	+Gz	Downwards
Downwards	+Az	-Gz	Upwards
Rightwards	+Ay	+Gy	Leftwards
Leftwards	-Ay	-Gy	Rightwards

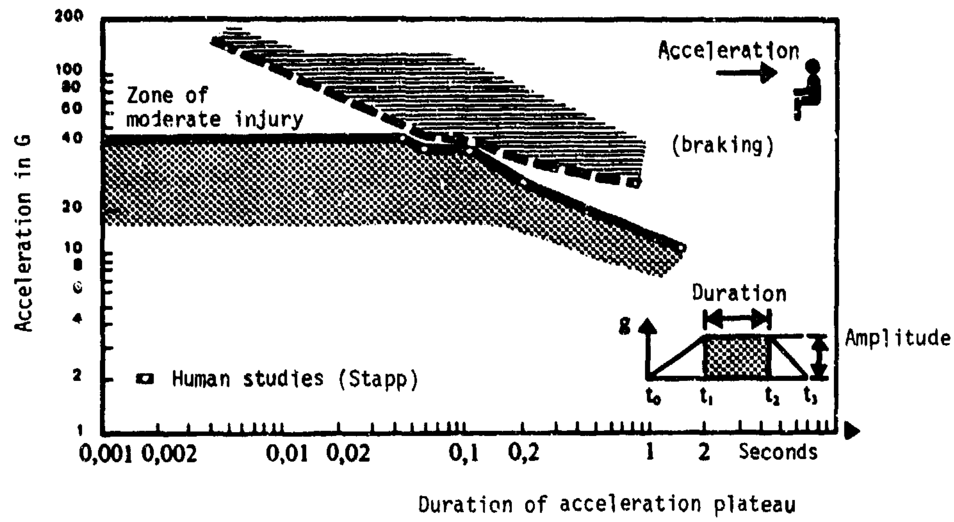


Figure 48. Tolerances for -Gx accelerations (from Stapp, 233).

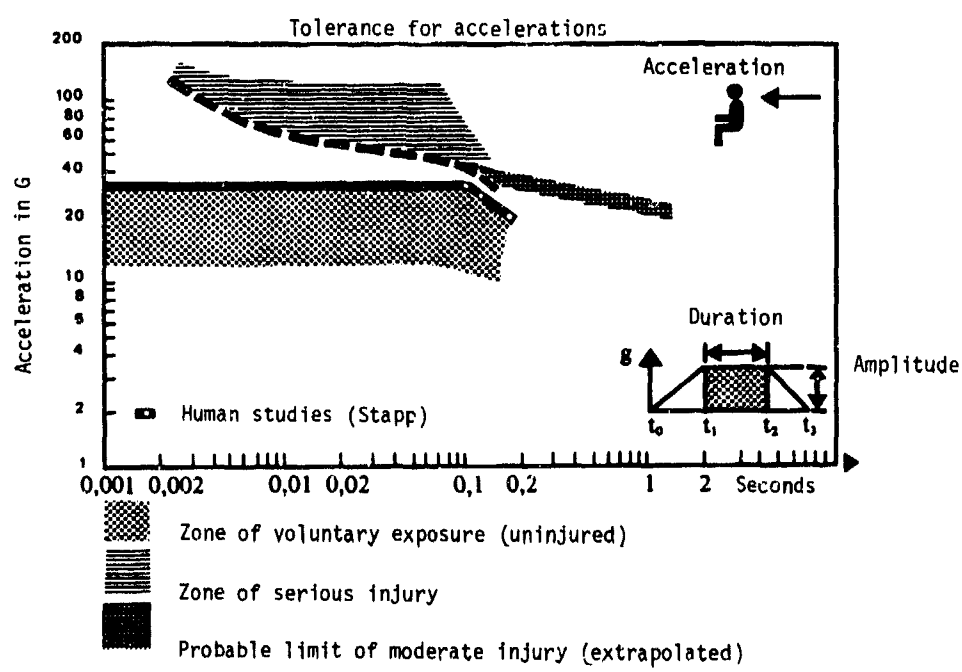


Figure 49. Tolerances for +Gx accelerations (from Stapp, 233).

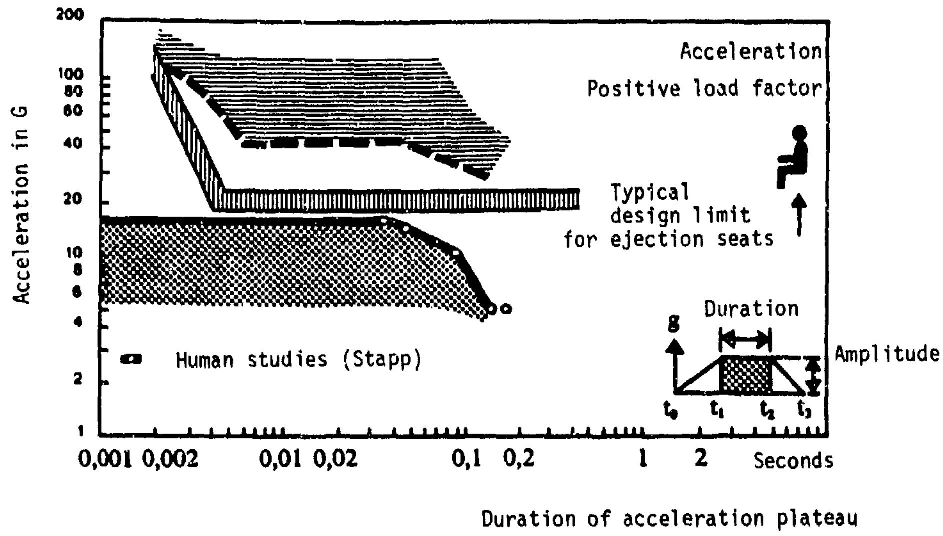


Figure 50. Tolerance for +Gz accelerations (from Stapp, 233).

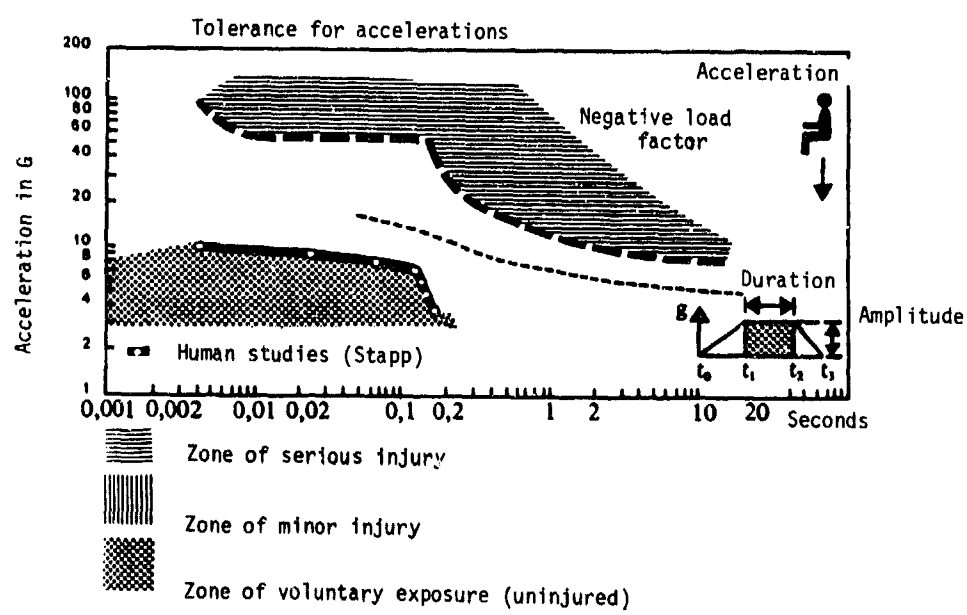


Figure 51. Tolerance for -Gz accelerations (from Stapp, 233).

It will be noted that the Z axes for the aircraft and the pilot are of opposite sign. Accelerations in the +Gz sense result in an inertial force in the head-to-seat direction, which tends to force the pilot into the seat and to compress the vertebral column.

It is almost certain that repeated microtrauma associated with accelerations has an injurious effect on the spinal column. Experimental studies in animals exposed to accelerations of long duration in the +Gz axis (several hours) have produced evidence of deterioration which consists mainly of lesions in the ligaments surrounding the disc. This may partly explain the development of painful symptoms and, later, of arthritis of the spine. It must be noted that an aerobatic manoeuvre often evokes the first episode of pain from a thoracic or lumbar arthritis which has hitherto been latent.

Accelerations can reach high levels during some manoeuvres in flight; tight turns, recovery from dives, combat. In these +Gz accelerations, the inertial force also acts on the hydrostatic column of the large blood vessels. These effects are primary. They reduce the perfusion of the upper vascular beds, and in particular of the brain, leading to visual disturbance which appears at about 4 G and the risk of loss of consciousness at about 5-6 G. They also increase blood pooling in the pelvis and the lower limbs.

Transverse (±Gx) accelerations arise during catapulting from or landing on aircraft carriers and in certain types of spin in modern aircraft. In astronautics they occur during rocket launch and during the re-entry of the spacecraft into the atmosphere. They act at right angles to the axis of the spine, and tolerance for them is, in consequence, higher.

It will be remembered that human tolerance of accelerations is inversely proportional to their intensity, to their duration, and to their "abruptness". This term refers to the rate of onset of the acceleration, and is called "jolt" by English speaking authors. It is the first derivative with respect to time of the acceleration and the second derivative of the velocity. It is important to take this factor into account in the study of the physiopathological effects of very high accelerations (Fig. 47).

Figs. 48-51 summarise tolerances for the various types of acceleration that commonly occur in aviation. Their intensity is generally modest, but their time of application is long; greater than 1 second.

4.1.2. Vibrations

Vibration consists of a series of displacements of a mass in both directions from its equilibrium point. These displacements can, of course, be characterised by their frequency, their amplitude, and their velocity (or better, by their acceleration).

In aeronautics, we are concerned with vibrations produced when an external force sustains the motion. They can be mechanical and originate from the engines or the rotor of helicopters, when their frequency is high or they may be aerodynamic and associated with the flow of air over the aircraft surfaces. They are particularly intense during flight through turbulence. Their frequency lies between 2 and 20 Hz.

Some vibratory phenomena having a frequency of around 1 Hz are known as "induced oscillations" (French "pompages") and may appear in combat aircraft at speeds of 500 knots or more. They can lead to fractures of the thoracic spine or to herniation of the lumbar discs. Accordingly, vibration represents a constant stress factor in aviation, which is difficult to eliminate and particularly injurious.

The human body has two principal resonance bands:

- at around 5 Hz, related to the shoulder girdle and the thoraco-abdominal system including the viscera

- at about 11 Hz, related to axial compression between the buttocks and the head.

At these frequencies, there is amplifcation within the body of the energy supplied by the vibrations, and it is in this band of frequency that tolerance is lowest. Unfortunately, it is also at these frequencies that the majority of vibrations in flight occur, especially in helicopters. It is now well established that prolonged and repeated exposure to vibrations, even of small amplitude, give rise to lesions in the bones and joints, particularly those of the lumbar spine.

The problem of reduced spinal mobility is twice as common in helicopter pilots as in the normal population. This can very probably be attributed to the repeated microtrauma caused by vibrations, and to the asymmetric posture adopted by the pilot with respect to the controls, which reduces the bracing efficiency of the paravertebral musculature.

As far as tolerance is concerned (Figs. 52 & 53), we must define a limit of comfort (of great importance because discomfort affects the whole of human performance) and a limit for the appearance of lesions. The time factor is of great importance in the latter case because accelerations of 2-3 G can be tolerated for several minutes, but over 24 hours, only a few hundredths of a G are acceptable.

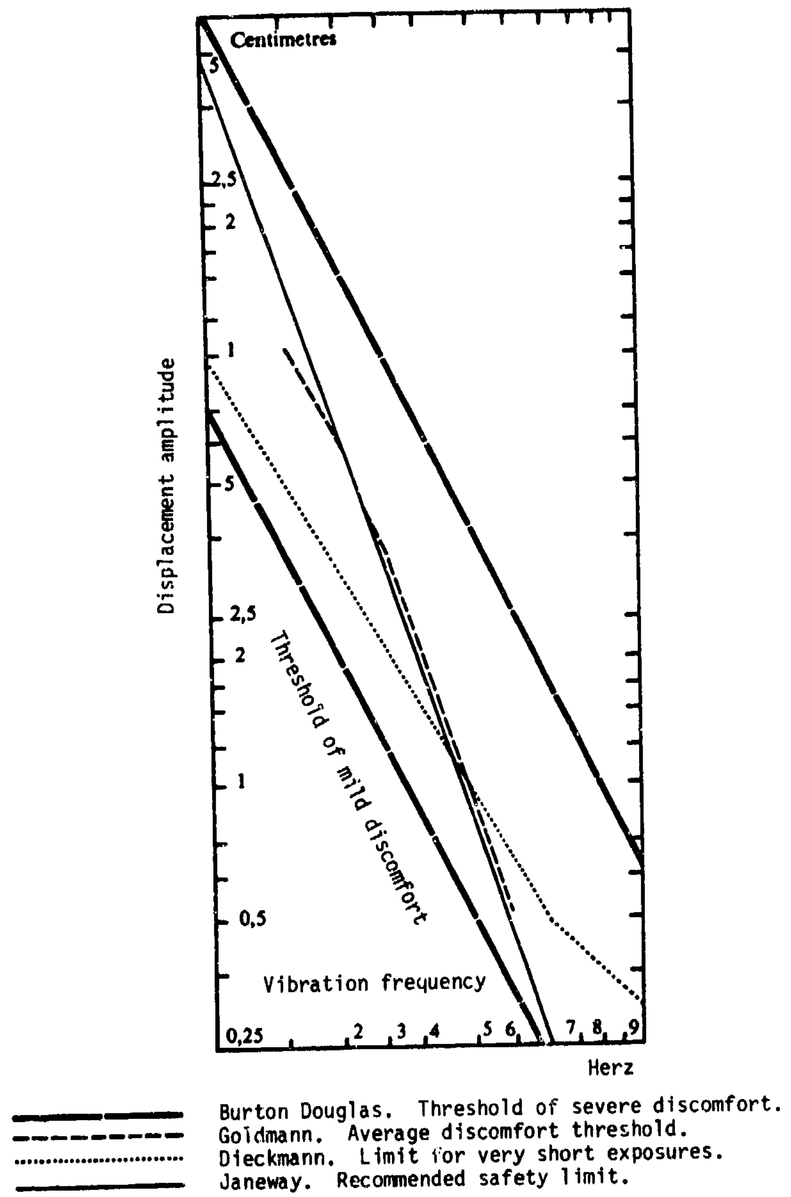


Figure 52. Curves of subjective tolerance for vertical sinusoidal vibration.

For vibrations in the $\pm Gz$ axis, the tolerance of a standing or sitting subject is at a minimum between 4 and 8 Hz. Below 4 Hz it is proportional to 1/f and from 8 to 100 Hz it is proportional to f.

4.2. FACTORS IN ACCIDENTS

Accidents give rise to very high accelerations, the duration of application of which is very short (less than 0.2 seconds). These are known as impacts.

The main characteristic of these forces is that they do not produce disturbances of physiological regulation (because their duration is too short) but mechanical effects. These can be fatal either immediately or after some delay, or can cause injuries which eventually heal (contusions, haematomas, fractures, dislocations).

The intensity of these accelerations is also very high, and their duration and rate of onset (jolt) are of considerable importance.

From the existence of two resonance bands in the human body (see Para 4.1.2.) it can be predicted that the transmission of forces within the body will be attenuated for very brief accelerations (less than 0.01 seconds) but that it will be amplified when the accelerations are of longer duration. At the same time, if the rise time of acceleration is short with respect to the natural period of the body (high jolt) large overshoots can occur.

All that has been said about the human body is also true of the materials which separate the pilot from the structure of the aircraft. In the case of an ejection seat, a poor cushion can transform a tolerable acceleration into a dangerous force.

Finally it is important to take account of the surface on which the inertial forces act. The effects become less serious as the body area over which the force is distributed is increased.

4.2.1. Ejection

The abandonment of a high performance aircraft flying at high speed is only possible by the use of an ejection seat. Ejection requires the application of a large force producing a +Gz acceleration of high intensity (more than 15 G) but with a very short time of application (between 0.2 and 0.5 seconds). Initially, the force acts solely in the longitudinal axis of the body, but it then becomes complex because of changes in the flight path of the seat and of braking.

It must not be forgotten that after the separation of the pilot from the seat, he becomes a parachutist. He then experiences:

- the opening shock of the parachute (8-10 G for 1 second for a descent from 15000 feet)

- possible landing injury which will be more likely if the pilot is not well trained in parachuting. Under ideal conditions, by day as well as by night, the deceleration experienced upon ground impact is of the order of 2-5 G for 0.1-0.4 seconds.

Despite the reliability afforded by successive refinements and by the automation of the different stages, ejection carries a major risk to the thoracic spine and traumatic lesions are frequent.

4.2.2. Crashes

During forced landings away from prepared runways, the pilot is exposed to complex accelerations of a very high amplitude (for example, 100 G). The duration of the deceleration is, however, very short and is measured in milliseconds. For this reason very high accelerations can be tolerated. Moreover, cases are known of survival after accidental falls during which accelerations in the -Gx axis reached between 150 and 250 G for approximately 0.01 seconds.

However, Fig. 49 shows that there is a large difference between the zone of serious injury and the zone of voluntary exposure not producing lesions (45 G), and it is difficult to predict the exact shape of the tolerance curve.

It is obvious that the tolerance values quoted apply only to subjects properly supported in their seat by an adequate restraint harness.

In summary, the spine of a pilot is subjected to two types of stresses:

- the first are an inherent accompaniment of flight; they are of relatively low intensity and their effects are related to the time for which they act; they represent the problem of fatigue of materials

- the second are uncommon, but of very high intensity; their effects are related to the mechanical strength of the spinal column, and they can lead to fractures. They represent the problem of the strength of materials.

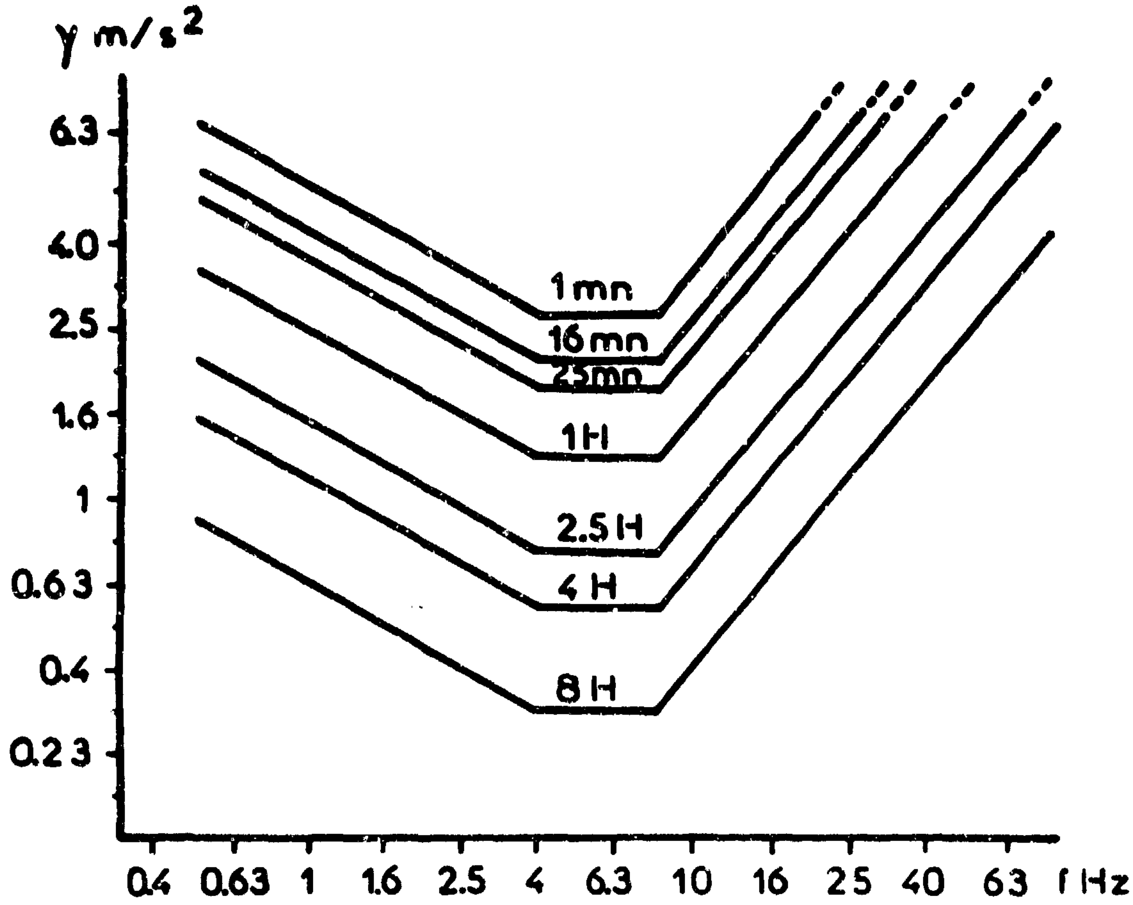


Figure 53. Tolerance for sinusoidal vibration.

Relates to tolerance limits for the appearance of fatigue and impairment of psychomotor performance.

To obtain values for "limit of voluntary exposure" multiply value by 2 (+ 6 dB).

To obtain values for "reduced comfort" divide values by 3.15 (-10 dB).

CHAPTER 5 - TRAUMATIC LESIONS OF THE SPINE IN AVIATION MEDICINE

SUMMARY

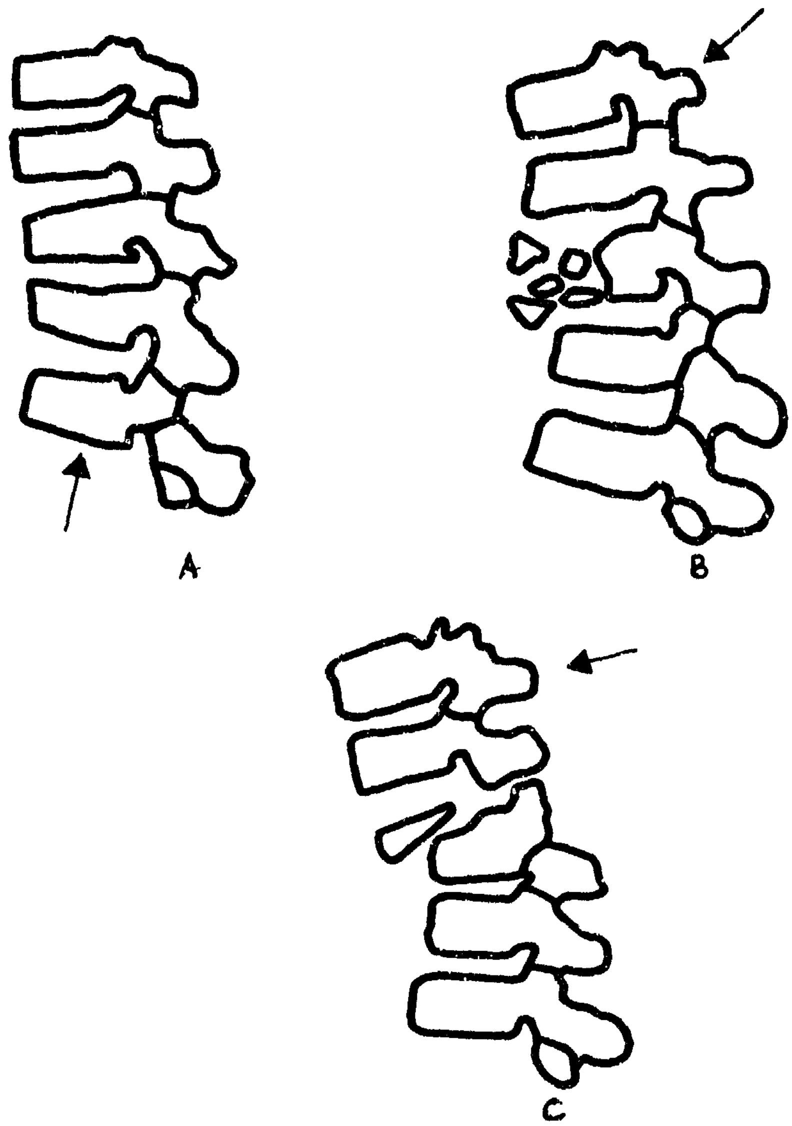


Figure 54. Mechanism of fractures of the thoraco-lumbar spine (after Watson-Jones, 448).

5.1. INTRODUCTION

R.P. Delahaye

In aerospace medicine, traumatic lesions of the spine and their sequelae, incidence, and diversity, together with aetiological, clinical, radiological, therapeutic and medico-legal problems, dominate the entire vertebral pathology of the aviator and the parachutist. Many of the traumatic lesions arise when the aircraft is in distress. There are several methods of escape.

The first, common to most types of aircraft, is a crash or emergency forced landing (light civil aircraft, gliders, commercial transport aircraft, some military aircraft).

The second is by parachuting. From a badly damaged propellor-driven aircraft, the pilot can leave the cockpit by his own efforts, if the speed of the aircraft is not great. By contrast, in combat flight using supersonic jet aircraft and delta wings, the high speeds require the use of an ejection seat for abandonment of the aircraft.

Since 1970 there have been reports from several fighter forces of rapid vibratory phenomena (induced oscillation) occurring in combat aircraft flying at high speeds, and fractures of the spine have been diagnosed.

Parachuting, which was at first restricted to military forces, had become by 1980 a genuine sport having some thousands of participants with enthusiasm for two techniques; precision landing on a target and in-flight acrobatics. Recently, group flights of parachutists ("relative flight") have produced a new class of traumatic lesions - collisions in flight.

After a review of theories of pathogenesis which attempt to explain the different types of fracture of the spine in aerospace medicine, we shall examine the different aetiological circumstances in which traumatic lesions occur (crash, parachuting, ejection, accidents in flight, accidents on centrifuges and sleds). We shall then consider the clinical studies, and recount the practical methods of examination that are so often neglected. Radiology must be carried out early, using optimal techniques to yield radiographs that with the clinical examiantions, will facilitate the establishment of an accurate inventory of the lesions. The after effects of trauma, which are numerous, merit detailed description, for they produce a very special clinical and radiological picture with which every flight surgeon ought to be thoroughly familiar.

5.2. THEORIES OF THE PATHOGENESIS OF FRACTURES OF THE SPINE

R.P. Delahaye and P.J. Metges

We shall distinguish between fractures of the thoraco-lumbar spine and those of the cervical spine.

5.2.1. Physiopathogenic Mechanism of Fractures of the Thoraco-lumbar Spine

The work of Watson-Jones (443) and of Nicoll (380) has given a better understanding of the physiopathogenesis of fractures of the spine. Watson-Jones considers three principal directions of actions of forces. Each has, in the thoraco-lumbar region, a particular anatomical and pathological significance.

5.2.1.1. Vertical compression of the spine acts on a normal column, or on one that is more or less supported by reflex contraction; a subject falling from some height and landing either on his feet or his buttocks, for example; a well-restrained sitting subject falling vertically (a helicopter in autorotation, for example). The compression causes a wedge shaped collapse anteriorly, at the point of least strength of the vertebral body (vascular zone). The posterior wall (see Chapter 5.5, below) remains intact, and the discs and interspinous ligaments are also spared (Fig. 54a). Lateral flexion of the trunk (Nicoll) in a standing or sitting subject gives rise to asymmetric vertebral collapse, primarily on the side of the flexion.

5.2.1.2. Forces Suddenly Applied From Top to Bottom and From Back to Front (Fig. 54b)

The spine is placed in severe hyperflexion or slight lateral hyperflexion. The angulation becomes so large that the lower anterior edge of the vertebra becomes wedged in the upper surface of the vertebra beneath it. The anterior corner often becomes detached. The intervertebral disc is torn, and sometimes destroyed. The interspinous ligaments are often ruptured.

This mechanism is encountered in its purest form during crashes, but may also be observed during difficult of heavy landings. Exceptionally, such hyperflexion could be a consideration in the dynamic phase of high speed ejections.

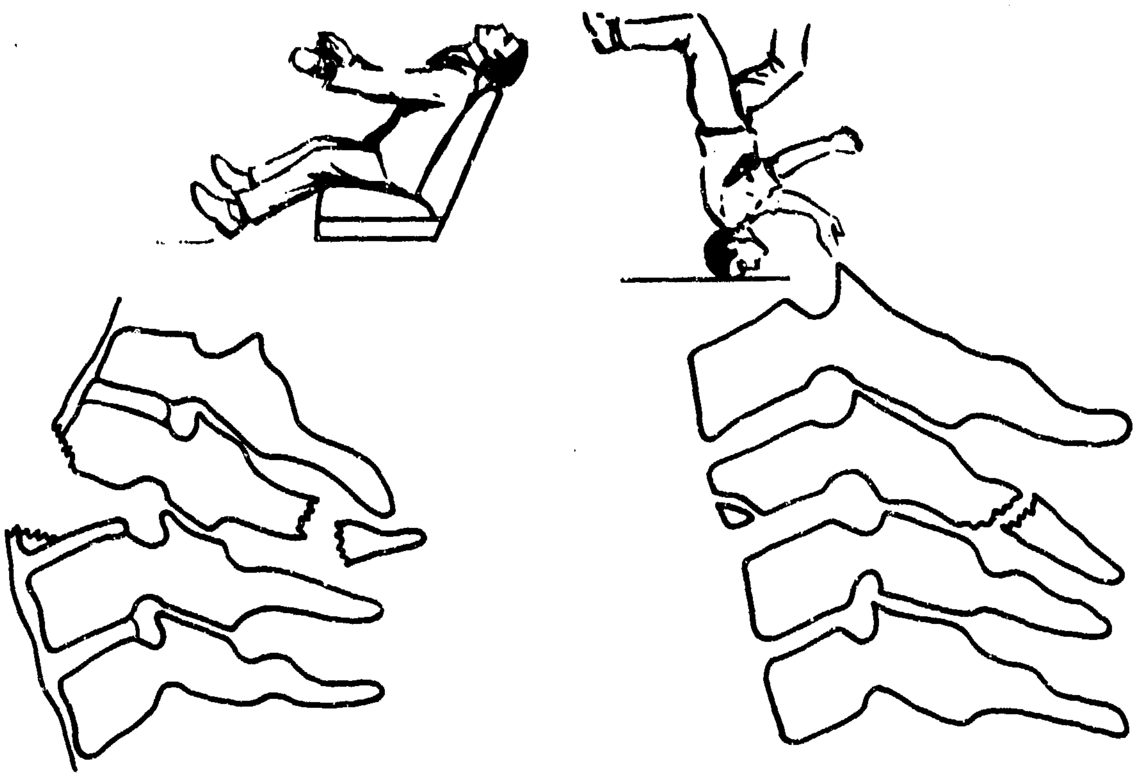


Figure 55. Mechanism of fractures of the cervical spine
a) - b) by extension (after Lavarde, 359).

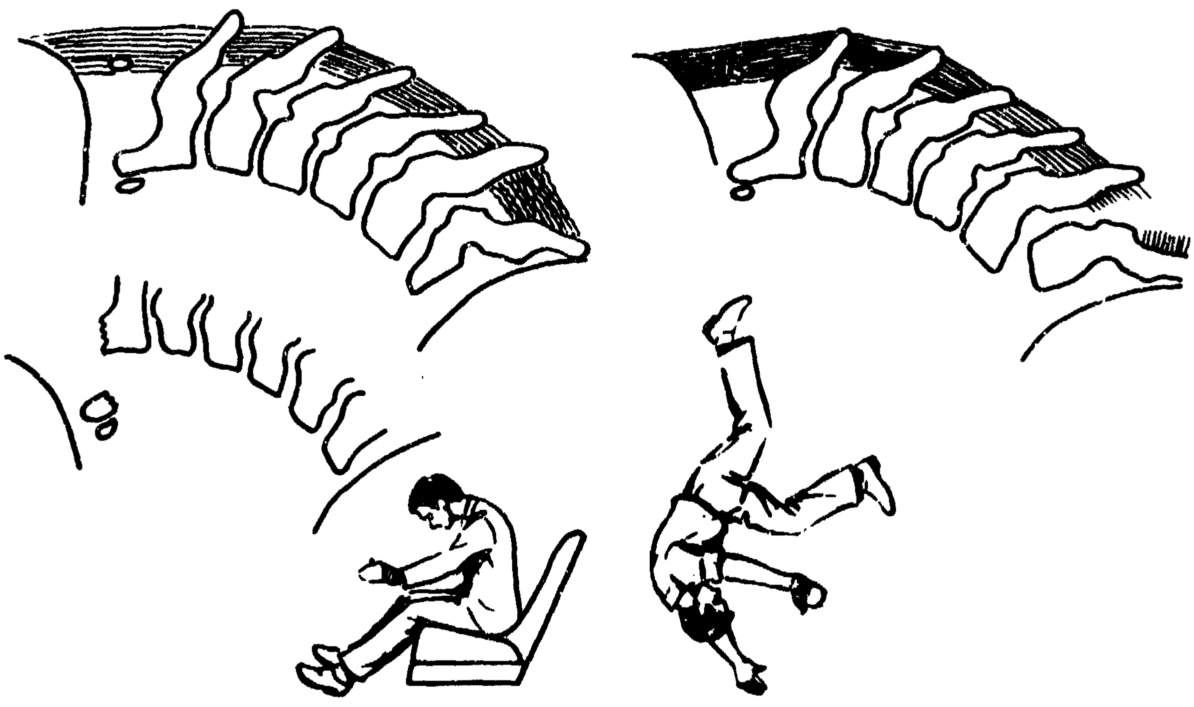


Figure 56. Mechanism of fractures of the cervical spine
c) - d) by flexion (after Lavarde, 359).

A posterior force acts perpendicularly to the spine on the upper part of the intervertebral body, which is driven forward. The line of the fracture passes through the entire vertebra from back to front. A dislocation is produced. Almost invariably, there is disruption of the posterior part of the interspinous and interapophyseal ligaments. It is sometimes associated with a displacement which involves rotation, either to the right or to the left, of the upper segment of the column. In that case lesions to the joints and to the vertebral bodies are always produced.

5.2.2. Physiopathogenic Mechanism of Fracture and Dislocations of the Cervical Spine

The mechanisms studied by Watson-Jones (448) and Nicoll (380) apply particularly to the thoraco-lumbar column. For the cervical spine, other factors are involved, either separately or in association with the preceding ones: lateral inflection and especially hyperextension (359, 449).

5.2.2.1. Lateral Inflection

In association with forward flexion, this position contributes to the development of asymmetric compression of the vertebrae. This lateral inflection may be observed, for example, in a parachutist, in a pilot during a crash in which the aircraft overturns and the fuselage breaks up, or in a helicopter accident. The head strikes the ground, one or more of the cervical transverse processes is broken, and a more or less complete paralysis of the brachial plexus develops.

5.2.2.2. Hyperextension (Fig. 55) (268)

This very special mechanism is particularly observed at the level of the cervical spine; a subject falling heavily backwards on his head; a pilot or passenger of a helicopter in a crash; a parachutist.

Cervical hyperflexion is, in general, limited to an angle of 20^{o} by contact of the chin with the sternum. However, the amplitude of the movement of extension sometimes reaches 90^{o} because of the extreme laxity of the joints and the ligaments. In order of increasing severity, the following lesions are produced:

- a primary rupture of the anterior longitudinal ligament
- simultaneous disruption of the anterior lower corner of the subjacent vertebra
- disc rupture and displacement
- damage to the posterior arch (fracture of the articular and spinous processes).

The severity of some cervical displacements caused by hyperextension is not always evident because they are spontaneously reduced. Most frequently, under the effect of the deceleration, nodding movements of the head occur successively from front to back and then from back to front, causing the classic "bell-ringing" motion, which is more rapid than the "whiplash" injury described by English speaking authors (446, 447, 448).

5.2.2.3. Hyperflexion (Fig. 56) (323)

Trauma caused by hyperflexion is not rare; as in falls from hitting the ground, or from diving into water; striking the head against the instrument panel or other obstacle. Loss of the protective helmet, which occurs in many cases, accounts for the co-existence of many major facial lesions.

5.3. AETIOLOGY AND PATHOGENESIS

5.3.1. Crashes

R.P. Delahaye and R. Auffret

SUMMARY

5.3.1.1. Crashes in Different Types of Aircraft

Although forced or crash landings sometimes occur on prepared surfaces, they frequently take place away from airfields, often on very rough terrain.

An elective crash landing may be the life-saving measure for light civil aircraft, for gliders, and for heavy passenger aircraft (either of the airlines or of the Forces). Helicopter accidents which come into this category are treated later (see 5.3.2.1.).

In military aviation, thanks to developments and improvements in methods of individual escape (ejection seat, parachute), the crash landing of aircraft with a high approach speed is generally a prohibited manoeuvre.

The pathogenesis of fractures of the vertebral column and the associated lesions is almost identical for all types of aircraft. A better knowledge of the development of the different events in a crash stems from the systematic laboratory study of automobile accidents, and from analysis of the various data obtained in the course of these experiments.

1. Light Civil Aircraft

Using the records of the Accident Investigation Office of the Inspector General of Civil Aviation (Ministry of Transport), Plantureux, Auffret and Lavernhe (182) have studied 1416 accidents occurring in light civil aircraft in France during the years 1974 to 1977 inclusive (Table 5.1).

The greater number of casualties (injured and killed) than of accidents is explained by the occurrence of multiple injuries and the presence of more than one passenger.

TABLE 5.1

	Accidents	Killed	Injured
Aircraft	275	243	291
Gliders	61	15	43
TOTAL	336	258	334

The spinal fractures found in 23 cases in 117 accidents during the last two years of the survey (1976-1977) were subjected to medical investigation by a new procedure. Their distributions are shown in Table 5.2.

TABLE 5.2

Cervical (3)	C5 C7	1 2
Thoracic (4)	T8 T11 T12	1 1
Lumbar (16)	L1 L2 L3 L4 L5	9 3 1 2 1

2. Gliders

Landing accidents generally occur with young, inexperienced pilots who, because of their poor judgement, miss their approach to the runway (43). At take-off (when the pilot may omit to retract the air brakes) crashes are less common. Loss of control (entry into autorotation and hitting the ground in a spin (6.5% of cases)) often leads to death or to serious injury (spinal fractures with neurological damage).

The vulnerability of the pilot situated in the front of the fuselage must be emphasised. In the case of frontal impact, the lower limbs are particularly exposed. Stedfeld (234) points out that gliding is entirely governed by the laws of aerodynamics. The pilot must adapt himself to these by sacrificing his freedom of movement and the comfort of his posture. In modern gliders, the pilot may lie supine (dorsal decubitus).

Over several years, both at the Begin Hospital and the Dominique Larrey Hospital, we have followed 13 pilots who suffered spinal fractures as a result of gliding accidents. These lesions were located at the level of D12, L1 and L2. In all cases the injuries were multiple; fractures of the lower limbs (tibia, femur, calcaneum), fractures of the pelvis, injuries to the bladder and the urethra. Neurological complications (paraplegia, cauda equina syndrome) were frequent (5 cases out of 13).

3. Military Aircraft

This paragraph is restricted to conventioanl propellor driven or subsonic jet aircraft (fighters). We do not include transport aircraft - Transall or KC 135; DC 8.

From the statistics from the French Air Force for 1961 (47) we note that the frequency of fractures of the vertebral column is higher in jet aircraft, which confirms both older studies (1, 89) and recently reported findings (72).

TABLE 5.3

TYPE OF AIRCRAFT	NUMBER OF ACCIDENTS	CASES WITH SPINAL FRACTURE
Single engined Aircraft (T6, Broussard etc)	88	4 (4.5%)
Jet aircraft (Mystere, Fouga, Vatour, T33, F84 etc)	166	12 (7.2%)

From Grandpierre et al (112)

The fractures lie mainly at the lower thoracic/upper lumbar level (D11 to L2). Higher thoracic injuries are less frequent, and cervical lesions are rare (85, 114).

4. Passenger Transport Aircraft (Civil and Military)

In the absence of any method of individual escape before hitting the ground, a crash is the only way out in case of emergency. Depending upon the nature of the terrain and the configuration of the aircraft, the accelerations imposed vary in amplitude and in direction.

In major impacts, the inadequacies of seat anchorage to the floor leads to the piling up of passengers, still attached to their seats, in the front section of their compartment. In these cases of multiple trauma, fractures of the spine are sometimes seen, and are for the most part thoraco-lumbar.

5.3.1.2. Localisation of Spinal Fractures in Crashes

The study of different reports on crashes confirms the frequency of localisation at the level D10-L2 (65-75%). This non-specific characteristic of crashes recurs in all statistics on trauma published in recent years (139). Fractures at multiple sites are not uncommon. In several crashes of civil aircraft, we have noted an association between two levels; cervical and lumbar.

Fractures only of the transverse processes of lumbar vertebrae are generally multiple, and may be associated with other lumbar or thoracic fractures; they are not uncommon. We do not think, as do Barrie et al (12), that these fractures occur frequently and that they are an almost specific crash injury. In fact, it is nearly always direct trauma that gives rise to fractures of the transverse processes.

On the other hand we share the opinion of Drew et al (80) who, from the examination of many victims of aircraft accidents (Beechcraft, Cessna 337), stress the high incidence of neurological complications (paraplegia, cauda equina syndrome).

5.3.1.3. Lesions Associated with Spinal Fractures in Crashes

The analysis of the different lesions which result from a crash allow several syndromes to be defined, according to the part of the body injured by the displacement of an inadequately restrained individual.

1. Hip-knee syndrome (later known as the instrument panel syndrome), which comprises lesions of the knee (fracture or dislocation of the patella; fracture of the tibial condyle), of the hip (posterior dislocation; fracture of the neck of the femur), of the pelvis (fracture of the wing of the ilium, or of the iliac and ischiopubal rami), or of the femur (lower third or shaft).

2. Cephalic syndrome caused by impact of the unprotected head against the instrument panel or the front window (this is called, in automobile accidents, the windshield syndrome), which comprises cerebral concussion, fractures of the skull (vault and base), and fractures of the cervical spine by the whiplash mechanism. This aggregation of lesions carries a mortality of 80%.

3. Thoracic syndrome caused by direct impact of the thorax against the instrument panel or other parts of the aircraft (the "steering wheel" sydrome in automobile accidents) consisting of fractures of the sternum and the ribs, pneumothorax, haemothorax, rupture of the aorta and great vessels, rupture of the diaphragm, of the liver, and of the spleen).

5.3.1.4. Pathogenetic Mechanisms

1. Forces and Accelerations in Crashes

The accelerations in a crash can reach very high amplitudes (100-500 G) in a very short time (0.01-0.001 second). Such values have been measured in simulated crashes of light aircraft. The accelerations are linear (longitudinal, transverse) as well as angular, or several types may be combined.

The forces transmitted to the occupants of the aircraft are subject to extremely wide variation, and depend on a number of factors (106):

- their attenuation and absorption by structures located between the ground and the occupant, by the surfaces of the aircraft colliding with the ground

- the distance of the occupant from the point of impact

- the surface, configuration and strength of objects against which the individual is decelerated

- the attenuation and absorption of force by the body of the pilot or passenger who is the victim of the crash

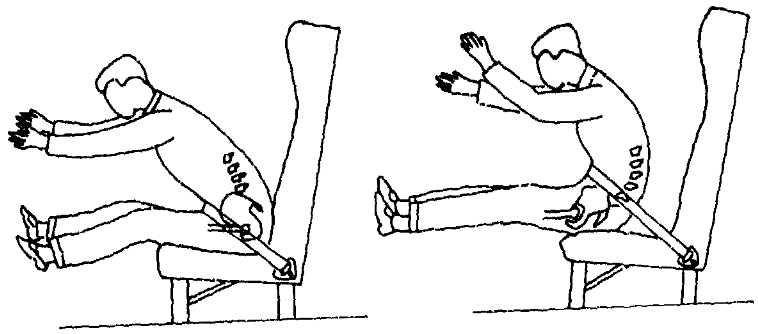


Figure 57. Effect of deceleration when the body is restrained by an abdominal belt (after Fryer, In Gillies, 106).

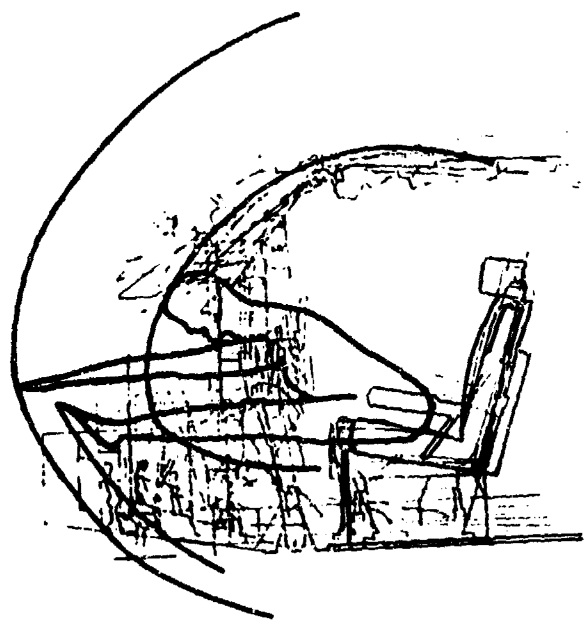


Figure 58. Area of forward displacement with an abdominal belt, from patterns seen in 11 aircraft accidents (from Swearingham, 140).

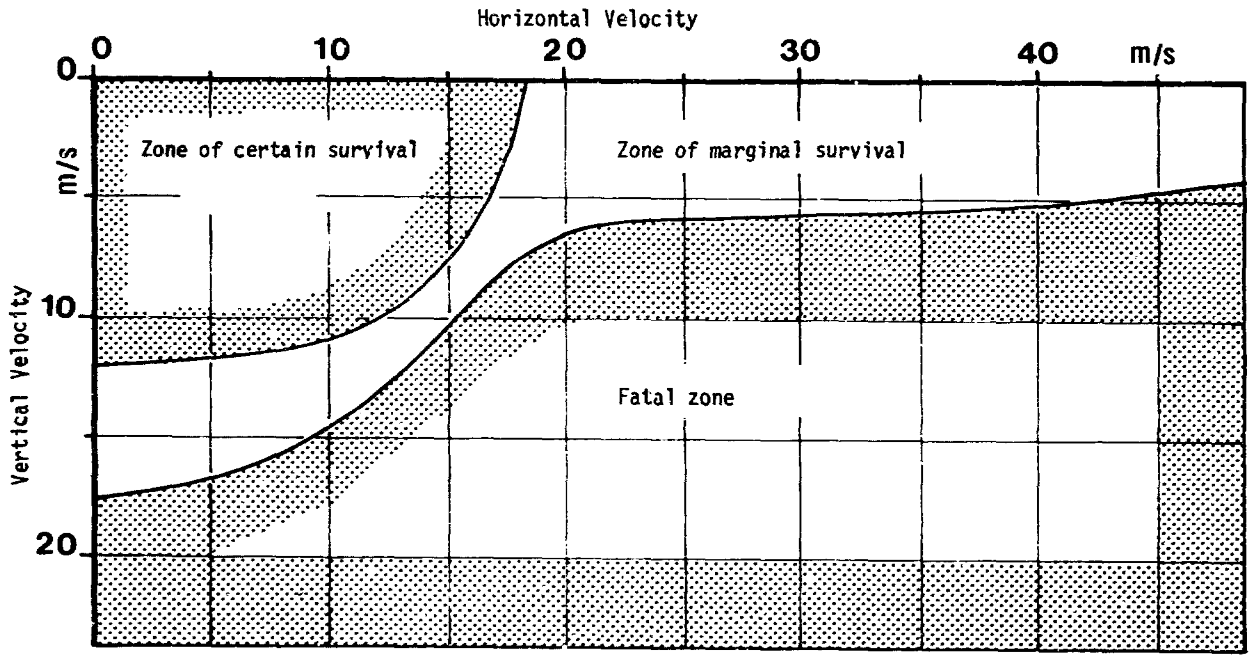


Figure 58a. Survival curves as a function of impact velocity (after Johnson and Mamalis, 140).

- the rate of application of the forces and their frequency characteristics

- their duration.

It is difficult to reconstruct precisely the circumstances of an accident, or at least of the last moments preceding the crash. It is often impossible to elicit from the seriously injured victim his precise position, the manner in which he was seated, and the degree of restraint.

2. Pathogenesis of Spinal Fractures Produced by Crashes

Watson-Jones, in Great Britain, was the first to demonstrate the relationship between the mechanism and the lesions, based upon observations of 1058 spinal fractures occurring, for the most part, in the Royal Air Force during World War II. He was concerned with spinal fractures of varying severity produced by flexion.

The curvature of the spine is modified according to the position of the harness. At the moment of a crash, the pilot tightens and locks his straps. He braces himself against the rudder bars, and supports his back against the back of the seat. In this seated position the physiological thoracic kyphosis is little changed, but there is a diminution in the lumbar lordosis. Since 1961, we have been able to confirm this in subjects sitting on aircraft seats in the radiology department (52, 57).

When the crash occurs, there is an abrupt deceleration which causes hyperflexion of the trunk. The restraint harness plays an effective protective role by preventing the pilot from being thrown against the instrument panel (Fig. 57). Depending upon the degree of restraint and the height of the fixation point of the harness, flexion of the spine occurs either at the junction of D12 and L1 or higher in long limbed individuals (D2-D7).

Crash fractures accord with the mechanisms described by Watson-Jones (see 5.1.). They are essentially related to hyperflexion associated with the application of a force causing an acceleration in the +Gz axis. For this reason, we do not think that the separate category of fractures due to the seat belt (described by American authors) deserves to be recognised and included (187, 257, 271, 281, 441). Cervical lesions do not occur in crashes except in very special circumstances; these usually involve a direct blow to the cervical column or to the head, or more rarely whiplash. It is certain that in light aircraft with seats the height of which is less than the sitting man, the risk of cervical lesions is much greater.

3. Pathogenesis of Lesions Associated with Fractures of the Vertebral Column

Restraint by effective harnesses has proved to be indispensable, and by 1937 its value was recognised by many air forces. The large number of crashes occurring during the Second World War confirmed the need for a correct restraint system. Research laboratories concerned with automobile accidents have, in well-documented studies, advanced our knowledge. In particular, cine-photography of the seated subject exposed to the forces of collision has been carried out during vehicle impacts. Thanks to cine films (231) it has been possible to define the different events. The work of Ewing (84, 86) has led to a better understanding of these phenomena.

If the passenger or the pilot is not supported by an effective restraint system and the aircraft crashes, the following events occur:

- the subject slides forwards in his seat until his knees make contact with the instrument panel or the seat in front of him (instrument panel syndrome)

- the thorax flexes forward. The head comes into contact with the instrument panel or with the seat back

- the lower part of the body continues its downward movement ("submarining", producing hyperextension).

According to Snyder, there are three basic problems related to protecting the occupants (231).

a. Limiting the movement of the individual (pilot, crewmember, passenger) to prevent contact with structures capable of causing injury (Fig. 28b)

b. Limitation of acceleration, particularly in the Gz axis, by the use of a suitable seat cushion.

c. Reduction of movements between adjacent parts of the body. Head movements in whiplash can be reduced by using a high seat back which prevents hyperextension.

A seatbelt is effective if it prevents the subject being thrown from the seat. However, it cannot always prevent impact with other structures of the aircraft (140). Fig. 58 (from 140) depicts the relationship between speed of impact and survival.

5.3.2. Helicopter Accidents

B. Vettes and R.P. Delahaye

SUMMARY

5.3.2.1. Introduction

Since the end of the Second World War, the helicopter has made tremendous strides in the fields of civil and military aviation.

Civil operations are very numerous and extremely varied; rescue from mountains or from the sea, evacuation and transport of the sick or wounded, "door to door" transport of personnel (USA), agricultural use (dusting of insecticides or fungicides over large areas), transport of large items; forest, highway, maritime, and herd surveillance. Between 1967 and 1977, the civil helicopter fleet in the USA increased from 487 aircraft to 7160.

In the military field, the helicopter has demonstrated the range of its potential uses; parachuting, transport of commandos, anti-tank combat, maritime surveillance, anti-submarine warfare, evacuation and transport of casualties.

5.3.2.2. Helicopter Accidents

5.3.2.2.1. General

This increasing use of helicopters is explained by their manoeuvrability; vertical take-off and landing; hovering flight. Moreover, the helicopter does not need a very sophisticated ground base: a large terrace, a hospital forecourt, or a sports field will suffice as a heliport. Unfortunately, because of these same qualities and of the ever more dangerous nature of the missions, helicopters are involved in many accidents, often very serious ones.

The tragic toll of many victims killed, burned, drowned or injured is explained in part by the lack of an inflight escape system, and by the frequent inadequacy of protection against the effects of crash and fire.

Helicopter manoeuvres take place most often at low, or at very low, altitude. Thus, the smallest pilot error, a malfunction of the flight controls, a loss of control, damage to or loss of the main or tail rotor, mid-air collision, explosion due to fire, or "freezing" of the transmision inevitably causes the aircraft to descend and strike the ground or the water.

The low strength of the fuel tanks all too often leads to their rupture on impact in a crash and partly explains the sudden development of a fire that leaves only a few burnt pieces of debris (engines, magnesium alloy of the fuselage, charred bodies). Many drownings are caused by rapid sinking of the helicopter, from the inadequacy of flotation equipment, from the inability of the occupants to leave the aircraft rapidly, or from difficulties in rapidly releasing and deploying the pneumatic life rafts.

5.3.2.2.2. Statistical Studies

It is always extremely difficult to obtain statistics for helicopter accidents in the civil sector and to derive an accurate picture of the nature, incidence, severity and distribution of injury to the occupants (crew and passengers).

In the military field, whatever the country, these criteria are often better defined and analysed by commissions of inquiry.

TABLE 5.4

Accidents in USA (1964-75 inclusive)	Killed	Injured	Uninjured
Crewmembers	299	368	3449
Passengers	314	244	2390
TOTAL	613	612	5839

1. Civil Helicopters

Table 5.4 (from Snyder, 232) is based on the study of 3573 civilian helicopter accidents occurring in the United States between 1964 and 1975 inclusive; an average of 255 accidents per year involving 7064 people (an averge of 505 per year). Of these, 5839 (82.7%) were uninjured or only slightly injured. This percentage is little different from that observed in fixed wing aircraft during the period 1967 to 1976 inclusive (78.8%). The number of accidents changed from 222 in 1971 to 198 in 1975 and 304 in 1976.

Snyder compared the incidence of dead and injured in civilian helicopter crews and passengers. He used two particular measures; the annual index of mortality, obtained by dividing the number of deaths per year by the annual number of accidents, and the annual incidence of serious injuries, obtained by dividing the yearly total of serious injuries by the annual total of accidents.

The mortality index is always higher among passengers. On the other hand, the annual index of injury is always greater in crew members. Unfortunately, Snyder does not, in his important work (232) precisely state the distribution of lesions among the seriously and the slightly injured.

Table 5.5 depicts the statistical analysis of 91 civil helicopter accidents which occurred in France from 1972 to 1979 inclusive. It includes only the dead and injured from the 36 accidents which resulted in injury. The aircraft were completely destroyed, and this explains the small number of uninjured subjects. Among the injured there were 6 spinal fractures, the majority being at the level of D12/L1.

TABLE 5.5

Accidents to Civil Helicopters (1972-79 inclusive)

	Killed	Injured	Uninjured
Crew and Passengers	22	33	8

2. Military Helicopters

In the USA, Singley (218), Sand (202) and Haley (125) have established the type, incidence, and distribution of injuries in helicopter accidents in the United States Army.

In 50% of the cases the injuries were to the head and to the upper and lower limbs. Cranial trauma, multiple injuries to the limbs and burns were responsible for 70% of the deaths (202).

TABLE 5.6

AUTHOR	HALEY (125)	SAND (202)
Source	US Army	US Army
Period of Review	Jan 1967 - Dec 1969	Jan 1972 - Sept 1977
Accidents	2546	388
Personnel	11334	
Killed	1094 (9.6%)	133
Injured	2699 (23.8%)	934
Spinal Injuries*	525	94
Spinal Fractures	180	73

*Includes fractures, sprains and contusions

The incidence of spinal lesions (fractures, sprains, bruises) in helicopter accidents varies according to the source of the statistics. If their frequency is expressed as a proportion of the incidence of injuries, there is a range of 3 to 1 in the American studies:

Bezrech (27)	6%
Mattox (169)	13%
Sand (202)	10%
Haley (125)	19%

Fractures of the spine comprise a large part of the vertebral trauma in helicopter accidents, which varies from 25 to 77% of spinal injury in the studies analysed.

French Helicopters

Table 5.7 shows the annual rate of military helicopter accidents for the French Armed Forces from 1969 to 1979. Fourteen spinal fractures were noted among the 100 injured personnel.

5.3.2.2.3. Distribution of Vertebral Fractures

These occur most frequently at the level of the thoraco-lumbar junction (D12/L1), but involve D10, D11 and L2 equally. At sites between D10 and L2 they are sometimes accompanied by neurological lesions (paraplegia, cauda equina syndrome). These complications are not uncommon, affecting 3 cases out of 14 in the statistics from the three French Armed Forces. For several years, we have had the opportunity to follow at the Begin Hospital, several pilots from foreign air forces who have sustained irreversible neural lesions. These cases confirm our opinion that helicopter accidents are, of all the sources of trauma in aviation, those which produce most neurological complications.

Fractures in the thoracic region are not rare. On the other hand, cervical fractures are undoubtedly more common than the scrutiny of different statistics would suggest. As often as not, no systematic radiological examination of the cervical spine is carried out in the majority of civil helicopter accidents.

TABLE 5.7

YEAR	NO OF ACCIDENTS	KILLED OR MISSING	SERIOUSLY INJURED	SLIGHTLY INJURED
1969	3	6	1	3
1970	11	3	9	4
1971	15		4	5
1972	11	1		2
1973	9	7	3	7
1974	6	3	1	3
1975	5	7	2	3
1976	12	32	10	14
1977	2	5	3	
1978	9	11	4	16
1979	6	6		10
TOTAL	89	81	33	67

5.3.2.3. Different Categories of Helicopter Accidents

Helicopter accidents can be schematically divided into two categories according to whether or not the pilot remains in control of the aircraft at the time of impact with the ground.

5.3.2.3.1. Crash Landing with Autorotation

A crash in autorotation is to the helicopter what the forced landing (with or without the undercarriage retracted) is to the aircraft; that is to say, a life-saving manoeuvre. In fact, the only way to make a descent and landing after an in-flight emergency is to carry out an autorotation. Autorotation is a manoeuvre executed without the engine, during which the upward flow of air, passing through the rotor system, induces "free wheeling" of the blades during the descent of the helicopter. Immediately before the impact, the spinning of the rotor system is translated into lift, in proportion to the pilot's use of the pitch control (angle of attack of the rotor blade), thus performing a manoeuvre to ensure a reasonable rate of descent. Autorotation has only been studied as a means of reducing the ill-effects of loss of power in flight. If it is to be successful the following conditions must be satisfied:

- control of the helicopter
- sufficient speed and altitude before entering autorotation
- favourable landing terrain
- sufficient visibility and an appropriate flying technique.

In this case the aircraft lands with a relatively small forward velocity and a greater or lesser vertical speed. This can range from a normal landing to a hard or even destructive impact equivalent to a true freefall. Crashing backwards in autorotation accounts for about 42.3% of helicopter accidents (data of Kimball et al (151) for the American Army in the years 1970-72). The acceleration experienced by the occupants of the aircraft is largely directed in the longitudinal axis of the body (Gz) and it is understandable that the vertebral column should be greatly affected and directly threatened.

5.3.2.3.2. Crashes with Loss of Control

In-flight loss of control in a helicopter can result from loss of one or more blades from the main or tail rotor, as well as from mid-air collisions, from major damage sustained in combat, from fire or from explosion, or from freezing or seizing of the gearbox. The aircraft goes into a spin and can strike the ground at any angle of incidence. The damage is considerable, and the result is often a pile of twisted metal with a number of dead or severely injured personnel who have suffered multiple, non-specific trauma.

In addition, the loss of a blade in flight sometimes induces very severe vibration. In one accident reported in the United States, the accelerations generated were sufficient to cause rupture of organs in-flight and death of the pilot before impact with the ground.

Because of their elasticity and inertia on impact, the rotor blades can often pierce the cockpit, seriously injuring or decapitating the occupants and starting a fire.

5.3.2.3.3. Discussion of this Classification

This schematic division of crashes into ground impact in autorotation and crash with loss of control of the aircraft corresponds to a distinction made by American authors (250, 125).

These authors consider two types of accidents:

- crash with the possibility of survival

- unsurvivable crash.

In the first case the combination of all conditions is such that the forces transmitted into the aircraft, to the seats, and to the restraint systems (seat belt, harness) do not exceed the limits of human tolerance. The strength of the structure is great enough to prevent crushing of the occupants upon impact. Accordingly, it is justifiable to assume that there will be survivors. The chances of survival will be even greater if there are systems for crash attenuation, for flotation, and for prevention of fire.

In the second category (unsurvivable crash) the impact is extremely high, and forces transmitted are outside the limits of human tolerance. The landing attitude is abnormal and, most often, the aircraft explodes on hitting the ground.

The first type (crash with the possibility of survival) equates, in essence, to a crash following more or less successful autorotation, and the second to a crash after loss of control.

Haley (125) published a study concerning several categories of helicopter; light observation, light attack, heavy, and troop transport. In survivable accidents, he noted a large number of dead and seriously injured. From 1 January 1967 to the end of December 1969, 10,599 people (crew members and passengers) were involved in 2,388 survivable accidents. There were 439 dead, 2,633 injured, and 7,497 uninjured. On the other hand, 6% emerge uninjured from unsurvivable accidents (second type of Meek and Haley). In a total of 735 passengers in 158 accidents, there were 655 dead, 36 injured survivors, and 44 uninjured.

5.3.2.4. Pathogenesis of Vertebral Lesions

We shall distinguish between crashes in which the impact is purely vertical (accident in autorotation) and crashes with a significant horizontal component (second type, with a poor chance of survival).

5.3.2.4.1. Crashes with Purely Vertical Impact

Autorotative landings with heavy impact produce ideal conditions for the appearance of compression fracutres of the vertebrae, which correspond most often to the two first types described by Watson-Jones (448).

During an accident in autorotation, the posture of the pilot (who is totally preoccupied with the manoeuvre; bent forward watching the rotor tachometer and the landing point) is a factor favouring flexion of the spine. Under the effect of abrupt (Gz) acceleration, the spine flexes at its natural pivot point (the thoraco-lumbar junction), but this also applies to the zone between D10 and L2, in which fractures frequently occur in cases of autorotation.

Localisation in the lower lumbar region (L2 to L5) is due to vertical compression in the absence of shock absorption by the lower limbs. Fractures of this type may also be seen in crashes.

The following observations, reported by Delahaye et al (52) and by Italiano (137), perfectly illustrate this type of fracture.

Pilot of Alouette 2 - Loss of a blade from the tail rotor led to immediate disruption of the tail rotor unit. An "engine-on" autorotation was carried out in flat, open terrain from a height of 700 metres. The terminal phase was into wind, and the aircraft dropped abruptly in a level attitude from one or one and a half metres (an error caused by the presence of standing corn, which confused the judgement of distance). The pilot sustained two fractures, at D10 and D11.

Pilot of Bell 47G2 - During an engineering flight (test of the tail rotor), the aircraft suffered engine failure. The pilot reacted badly; his manoeuvres increased the rate of descent, and the speed of the main rotor fell off. The attempt at autorotation was made late. Radiography showed the L3 had sustained a wedge fracture at its anterior lower surface. An antero-posterior view confirmed an asymmetry (right lateral compression).

Pilot of Bell 47G3 - During a flight at low altitude, the helicopter crashed after collision with another aircraft. The pilot presented with a fracture of D12 (anterior wedge compression).

Pilot of Bell 47G4 - In the course of a reconnaissance flight the pilot made a sliding landing on the grassy track parallel to the take-off runway. During this manoeuvre the helicopter fell from a height of about 1 metre, the rear part of the left skid striking the ground. The pilot suffered a fracture of L1 with complete crushing of the body of the vertebra.

Pilot of Bell 47J - During a crop dusting flight, the transmission to the tail rotor broke. The helicopter fell from a height of about 1 metre. The pilot suffered a fracture of L1 (anterior wedge fracture).

5.3.2.4.2. Crashes with Significant Horizontal Components

Such crashes involve not only a large vertical acceleration, but also a horizontal or even lateral force. According to Hicks the incidence of fractures rises as the vertical speed increases, and also when there is a horizontal and lateral component at the moment of impact. The fractures seen are of different types and are not all confined to the thoraco-lumbar junction. They often involve the region from D3 to D8, and also the cervical region. They then consist of comminuted fractures, or fracture-dislocations, corresponding to mechanisms II and III described by Watson-Jones. Neurological complications are not uncommon.

The following observations illustrate this type of fracture.

Pilot in Alouette 2 - In horizontal cruising flight, the transmission shaft of the tail rotor snapped, and the rotor itself was lost. The crash, in a spin and with the engine on, occurred in particularly difficult terrain (mountains). The pilot sustained two fractures, at L2 and L3. A traumatic flaccid paraplegia rapidly developed.

Instructor and student pilot in Bell Jet Ranger 206B (cited by Snyder (232)) - After a mechanical failure followed by loss of power at a height of about 260 metres, the aircraft descended into a pine forest and fell from a tree. Despite the structural damage, the pilots were seriously injured. The instructor suffered a fracture-dislocation of L1 with compression of the spinal cord which led to paralysis of the lower limbs. Because of the multiple trauma to other vertebrae (fractures of the transverse processes of L1 to L4) and a crushed thorax, he did not survive his injuries. The student pilot suffered multiple vertebral fractures (of the body of L3 and of the transverse processes of L2, L3 and L4) and internal injuries. He survived but was left with a paraplegia.

Pilot in Bell 47G - During an attempted landing on a difficult mountainous site at an altitude of 2115 metres, the helicopter struck some rocks violently. The pilot's straps, which broke at impact, were cut clean through. The pilot had two fractures (D3 and D4).

In these last two cases, as a result of the disruption of the seat attachments and of the harness straps, the impact was produced directly by projection against obstacles. The harness plays an important role in crashes. Although it is unable to prevent the occurrence of vertebral fracture, it does stop the pilot from being thrown against the front part of the cockpit (see Chapter 5.3.1.).

Fractures of the lower cervical spine (C5 to C7) are not uncommon. The majority are caused by a mechanism of the whiplash type, or by direct blows. A systematic post mortem study of the spines of helicopter pilots and passengers has revealed a high incidence of fracture dislocations of C5/C6.

Conclusions

Methods of protection against helicopter accidents require research to reduce the risk of fatal accidents, which is 0.34 per 10,000 flying hours. Comparatively, an aircraft is much better adapted for crashing. The horizontal component of the impact is greater, there are numerous deformable structures, the pilot may have more control of the aircraft, and opportunities exist for in-flight escape (parachute, ejection seat). Thus, research is necessary to improve crash conditions in helicopters.

5.3.3. Ejection of Pilots from Combat Aircraft

R.P. Delahaye, R. Auffret and B. Vettes

SUMMARY

Ejections have not been a panacea.
However, they are complicated by experiences
and encompass a myriad of problems.

Major W.D. Harrison
USAF (127)

5.3.3.1. Introduction and History

Before the end of World War II, scientific studies by the Germans on the one hand and by the Americans and British on the other, had shown that pilot escape becomes very hazardous at high speeds. A large proportion of injuries and deaths occur during escape from combat aircraft. The collision of aircrew with the empennage of the aircraft above 300 to 400 km/h is often responsible for these accidents.

Usually, the pilot cannot abandon his aircraft by his own efforts because of the speed. Ejection by a powered seat is the only means of escape from the cockpit above a certain speed.

As early as 1939, Heinkel carried out the first studies using an inclined ramp; at first with dummies and later with men. Busch, a test parachutist, made the first successful ejection at a speed of 300 km/h. These trials led, in 1944, to the fitting of a Heinkel ejection seat successively to the Heinkel jet fighter (HE 162) and to the twin engined Messerschmitt 262. At the end of the Second World War, the 60 ejections that had taken place in the Luftwaffe allowed some very interesting data to be compiled (22).

In Sweden in 1942, a dummy was successfully ejected from a SAAB 17B bomber of the Swedish Air Force. In 1943, the first production ejection seat was fitted in the propellor-driven SAAB J21A fighter. The first human ejection occurred on 29 July 1946 following a mid-air collision.

In Great Britain, the first successful dummy ejection took place from a modified Defiant aircraft on 11 May 1945. On 26 June 1946, B. Lynch, a test parachutist, ejected from a Gloster Meteor fitted with a Martin Baker seat, at a speed of 515 km/h (22).

From the beginning, the US Navy used English Martin Baker seats, and the first ejection, by Lieutenant Furtek, occurred in November 1946. The USAF used a seat developed by the Aircraft Laboratory, and on 17 August 1946 Sergeant Lawrence Lambert ejected.

It was only in February 1948 that the test parachutist Robert Cartier became, at Chalgrove (UK), the first Frenchman to make an ejection, from a Gloster Meteor aircraft equipped with the Martin Baker seat (22).

Since 1946 more than 10,000 ejections have been recorded throughout the world (more than 4,400 of them in the USAF).

5.3.3.2. Principles of the Seat (Figs. 63 & 65)(2, 45, 52, 70, 73, 83, 106)

In order to avoid a collision of the seat and its occupant with the rear of the aircraft they must be given a velocity which becomes greater as the speed of the aircraft increases and as the dimensions of the fin become larger. The velocity of the seat at the moment of separation must be a minimum of 17 to 18 metres per second. To provide the acceleration which will allow the seat to achieve the desired speed, taking into account the very short time available, gas pressure generated by the combustion of one or more cartridges is used. Combustion takes place in a gun of which one part is fixed to the aircraft, the second being ejected with the seat. The accelerations reach 20 to 21 G with a duration of 0.08 to 0.1 second for simple guns, and 16 to 17 G with a duration of 0.18 to 0.2 seconds for seats with telescopic guns.

To increase the time of the acceleration and so to obtain a higher velocity of the seat in its trajectory, rocket sleds are currently used. On this type of seat, after the firing of the cartridges, the rocket ignites and the apogee of the trajectory is accordingly increased. In practice, this rocket applies a mean acceleration of 10 to 15 G for a supplementary period of 0.2 second. Furthermore, this time allows the so called "zero-zero" ejection (that is, from zero altitude and with zero speed). The apogee of the ejection path is high enough to permit the parachute to be deployed even when the aircraft has no initial forward speed. The firing of the ejection seat can be initiated either by a high (face blind) control, or by a low (seat pan) control.

5.3.3.3. Description of the Different Phases of Ejection (42, 52, 70, 100)

An ejection comprises different phases (Fig. 61):

Initiation

Seat Firing and Egress of the Man-seat Assembly

Seat Separation

Landing

Survival and Rescue

1. Initiation

Respect for the disciplines of ejection results from automatic responses acquired during training in cockpits or in simulators. Faultless knowledge of the actions to be taken is not of itself sufficient, because all the manoeuvres have to be performed in a very short time. Stress slows the speed of reaction in many pilots, and can even result in complete inactivity. One important factor which may delay the initiation of ejection must be stressed; the motivation of the pilot to retain control of the aircraft until the last possible moment to avoid hazard to the civil population on the ground or to bring back a prototype, the loss of which would be particularly serious for a test programme. Harrison (127) notes that in many ejections the pilot does not use the available time to position himself correctly. In all air forces, serious accidents and even deaths have occurred in pilots reluctant to use their ejection seat because their indoctrination was inadequate.

Nowadays, the pilots of combat aircraft have confidence in the ejection seat. Procedures have been simplified by the automation of different sequences, but whatever state of technical perfection the seat may have reached, the risk of fatality still exists. A pilot must be fully trained and know the procedures to be applied.

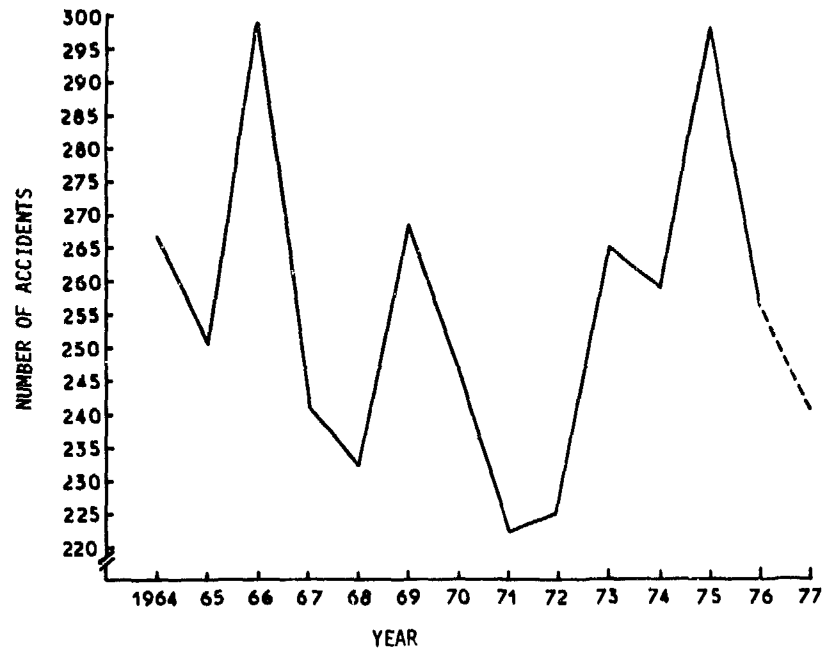


Figure 59. Distribution of civil helicopter accidents in the USA (from Snyder, 232).

Ejected weight: seat + pilot = 172 kg

— — — — Standard Mk 4 seat

Max. acceleration = 20 G
Seat velocity = 80 ft/sec
Onset rate = 240 G/sec

———— Rocket seat AM 6

Max. acceleration = 15 G
Seat velocity = 160 ft/sec
Onset rate = 200 G/sec

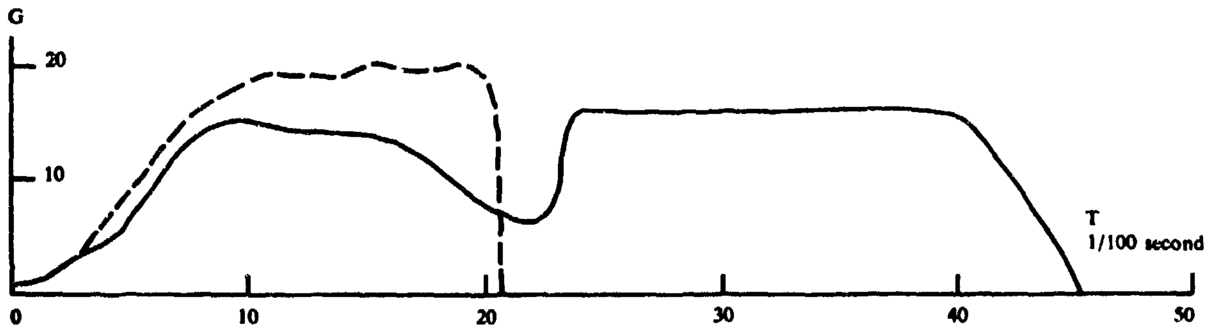


Figure 60. Time history of acceleration for ejection with 2 types of seat (standard Mk 4 and rocker AM 6).

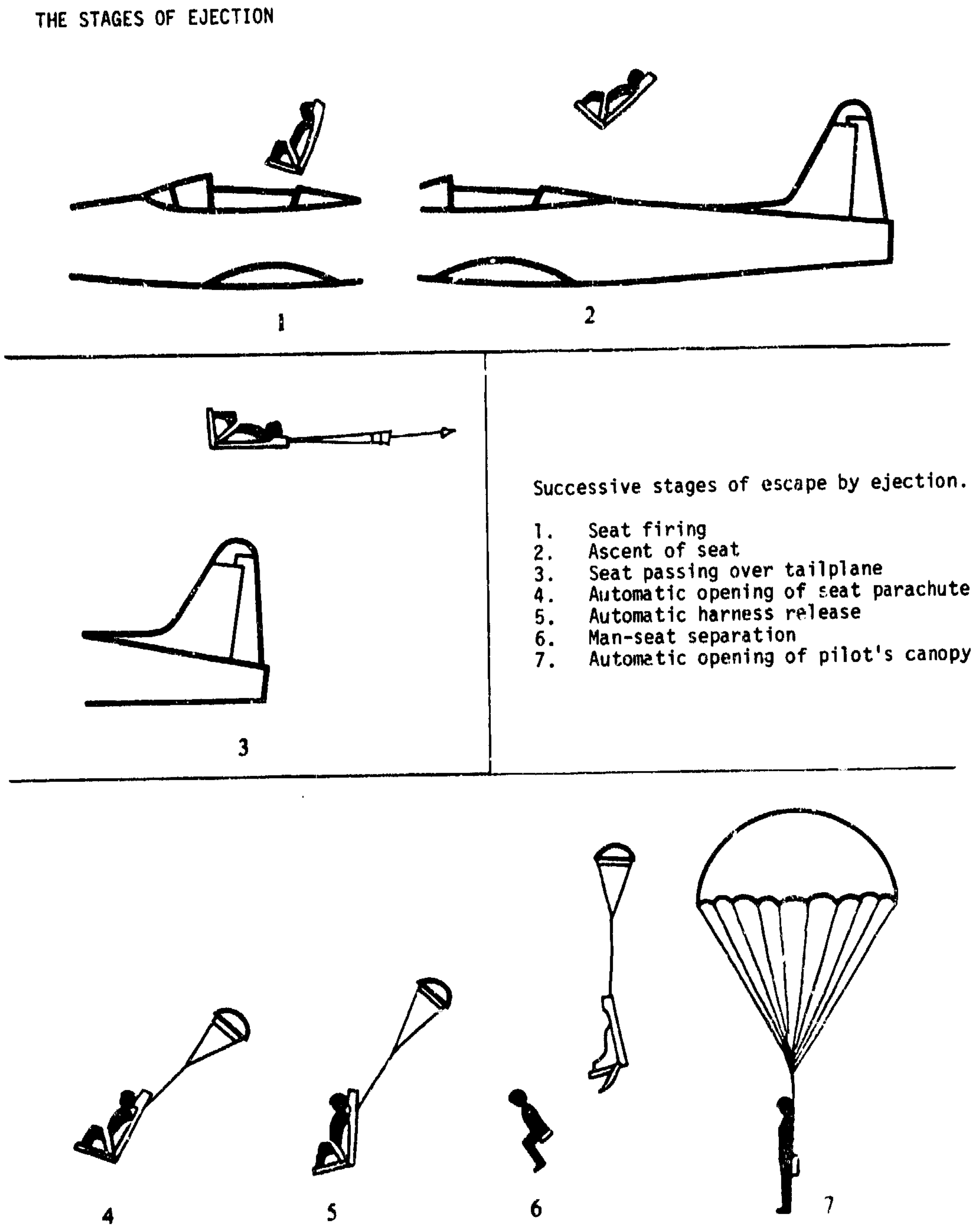


Figure 61. The successive stages of escape by ejection seat (from 52).

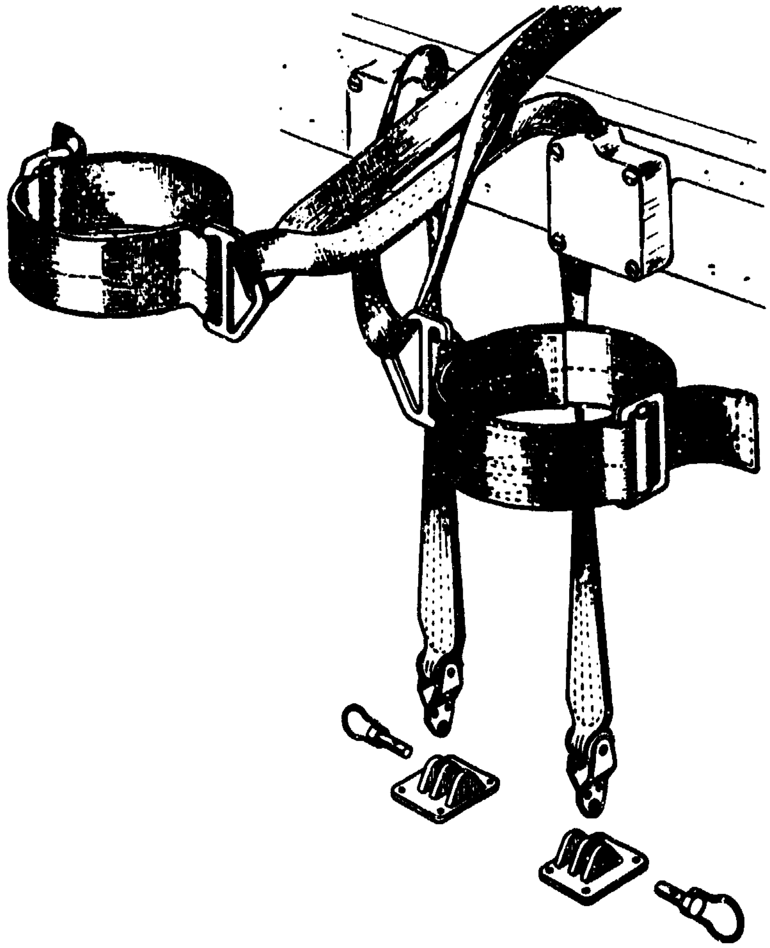


Figure 62. Leg restraint system.

If time permits, the correctly restrained pilot will lower the visor of his helmet and adjust the ejection seat to the position recommended in training. In seats with leg restraint systems, he must leave his feet on the rudder pedals (Fig. 62). For the Martin Baker AM 4 seat, the type most commonly used by the French Air Force, the pilot must remember that there is a delay of 1 second between the initiation of ejection and the firing of the seat. In the escape systems of newer aircraft (Jaguar, for example) this time is reduced to 0.4 seconds.

a. Use of the Face Blind Firing Handle (Figs. 63 & 64)

This method of initation is still frequently used in many air forces. It consists of a canvas or nylon screen, located in the upper part of the seat, which the pilot must pull with both hands, the palms being turned towards the face and the arms being practically parallel. An extraction force of 250 Newtons is required to trigger ejection. The face blind allows the pilot to adopt a good posture. Moreover, it protects the face and oxygen mask against the effects of windblast. The head is held against the head rest. The pilot should not lower his head to pull out the face blind. Without altering the angle between the forearms and the upper arms, he exerts a strong pull by simple downward rotation from the shoulders. The forearms reach the thorax and firmly hold the face blind, while the upper arms are firmly pressed against the body.

b. Use of the Seat Pan Firing Handle (Fig. 65)

This mechanism should be used in the following cases:

- failure of the face blind firing mechanism

- inability to reach the face blind (high +Gz accelerations)

The time gained by use of the seat pan handle instead of the face blind is theoretically of the order of 0.15 second. However, the extraction pull must exceed 400 Newtons (40 kg) and must be sustained for 1 second. Because of the lack of a face shield, this mode of operation is not ideal in cases where the speed is high at the moment of ejection. The body must be firmly pressed against the seat, the head properly positioned on the head rest, and the buttocks well dug into the seat. The pilot must not bend his head to look at the seat pan handle.

With one hand, the palm turned inwards, the pilot pulls the seat pan handle. The other hand grasps the opposite wrist. With the elbows held against the body, the forearms are pulled upwards.

Many fighter aircraft only have one lower control, which is sometimes placed in the armrest. The method of initiation of ejection and its influence upon the incidence of cervical lesions have been the subject of intense controversy in the aeromedical literature.

2. Seat Firing and Egress from the Aircraft (Fig. 60)

The seat, propelled by the firing of the cartridges, is projected upwards. Its movement causes the firing of another cartridge which ejects a small metal mass (the drogue bullet) connected to the stabilising parachute.

The first phase of seat movement is guided by the rails and successive segments of the gun. As soon as the man-seat assembly is exposed to windblast and subject to its own dynamics, rotation occurs; forwards if the speed is low (less than 200 knots), backwards if the speed is higher. At the same time there is lateral rotation. Some seats turn to the left and others to the right. An attempt is made to stabilise the trajectory on a given axis after leaving the aircraft by use of a stabilising parachute or drogue.

On rocket sleds, the centre of thrust of the rocket on the man-seat assembly is determined by calculation. The rotations of the seat and its occupant depend on the relative positions of the centre of thrust and the centre of gravity of the mass.

The seat, stabilised by the drogue, flies away from the aircraft. Its speed decays progressively until it attains the velocity of free fall. The time of descent for a Martin Baker AM 4 seat with stabilising drogue is 1 minute 30 seconds from 60,000 feet (18,288 metres) to 36,000 feet (10,972 metres), and 2 minutes 30 seconds from 36,000 feet (10,972 metres) to 10,000 feet (3,048 metres).

3. Separation from the Seat

In early types of seat the pilot had to separate himself from the seat. Five to ten seconds after ejection the pilot released himself to jettison the seat. The empty seat, braked by the stabilising drogue, receded rapidly from the pilot who descended in free fall. Opening of the parachute was then carried out manually. Various refinements have now made separation from the seat and opening of the parachute automatic, notably improving their safety (Fig. 58).

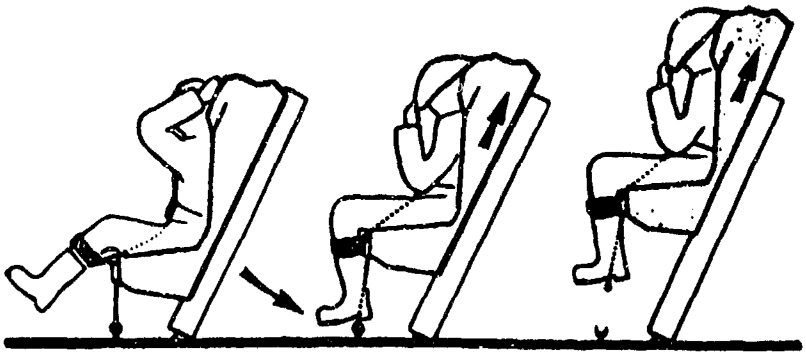


Figure 63. Initiation of ejection (face-blind).

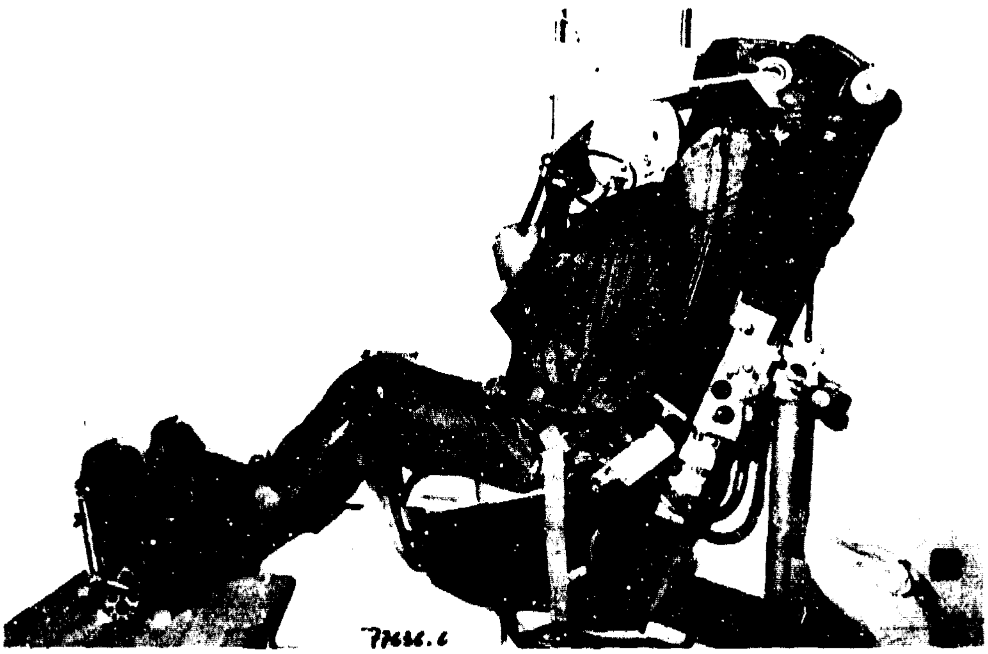


Figure 64. Initiation of seat ejection (by face-blind).

We shall consider two types of abandonment:

- At high altitude, the pilot descends on his stabilised seat to 10,000 feet (3,048 metres). At that height a barometric capsule triggers separation of the seat and the pilot and simultaneously initiates the opening sequence.

- At low altitude and at high speed an accelerometer senses the deceleration. This must be less than 4 G for opening of the main canopy to take place. This is because premature opening generates very large decelerations which are not compatible with the resistance of the human body and, above all, with the strength of the parachute.

The time of descent for an ejected pilot with an open parachute is 7 minutes from 10,000 feet (3,048 metres) to the ground; and 19 minutes from 36,000 feet (10,972 metres) to the ground. The latter is not advisable because of the ambient cold, of the small reserve of emergency oxygen, and of the large decelerations resulting from opening the parachute at high altitude, and, therefore, at a high free fall velocity (Figs. 66 & 67).

4. Landing

During his descent, the pilot has time to think and to analyse his situation. In fact, he is faced with many tasks.

To inspect and check the parachute, to detect damage or to steer it (if appropriate means are available).

To remove his oxygen mask at low altitude.

In the last 500 metres before reaching the ground or the sea, the pilot opens his survival pack which contains, among other things, an automatically inflating life raft. This dinghy remains connected to the pilot by a lanyard 5 metres long. In the latest escape systems, this sequence is sufficiently independent for the pilot not to be occupied by this last-minute manoeuvre. This improvement will certainly decrease the number of spinal fractures in ejected pilots, because statistical analysis shows the highest incidence of vertebral fracture in those pilots who have not remembered to release their survival pack. The explanation is simple. The mass of the survival pack is on average 8-10 kg, which is an addition to the weight of the pilot when he strikes the ground.

The pilot reaches the ground under conditions very different from those of the professional parachutist. Flying personnel are poorly trained in the techniques of parachuting. In certain air forces student pilots sometimes jump before attaining their wings to familiarise themselves with the conditions of landing. However, not all countries employ this questionable form of training because, among other things, it carries the risk of loss of expensive personnel from injuries to the spine and lower limbs. What is more, ejection often occurs a long time after the period of training. The ejected pilot chooses neither the time of escape nor the terrain. Night descents, strong winds, and landings on rough ground or in forests are not uncommon. Landings in water lead to drowning if the pilot has lost consciousness.

The parachute in general use has a reduced canopy area (40 m^2 instead of the 60 m^2 used by French airborne troops). The landing speed is thus greater than that of the professional parachutist (34, 52).

It is necessary to emphasise certain patholgical factors. The automatic operation of the different sequences of an ejection reassure the pilot, who is often very tense and distracted. After conditions that are very disturbing to some pilots, the problem of landing appears secondary.

5. Survival and Rescue

In peacetime rescue is rapid, thanks to aerial observation and spotting (generally by a crew member), and by the use of helicopters. In more than 65% of cases the ejected pilot is recovered in less than 2 hours.

During hostilities, the tactics followed for locating and recovering an ejected pilot greatly depend upon the weather (rain, snow, wind), the effectiveness of radiocommunications, the capacity of the pilot to survive, and the closeness of the enemy (Harrison, 127).

5.3.3.4. The Different Types of Ejection (9, 52, 70)

1. Normal Configurations

The aircraft is flying straight and more or less level and with a load factor close to unity. The pilot is correctly placed on his seat at the moment of ejection. All other configurations are abnormal.

Figure 65. Initiation of ejection by seat pan firing handle.

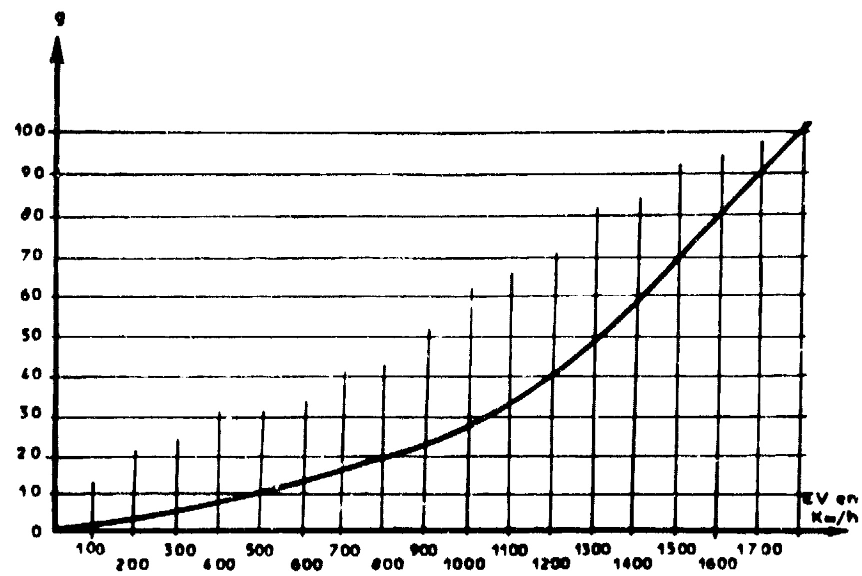


Figure 66. Maximum peak deceleration related to equivalent air speed (EV) for an assembly with a frontal area of 6.6 m^2 and a weight of 150 kg (after Mohrlock).

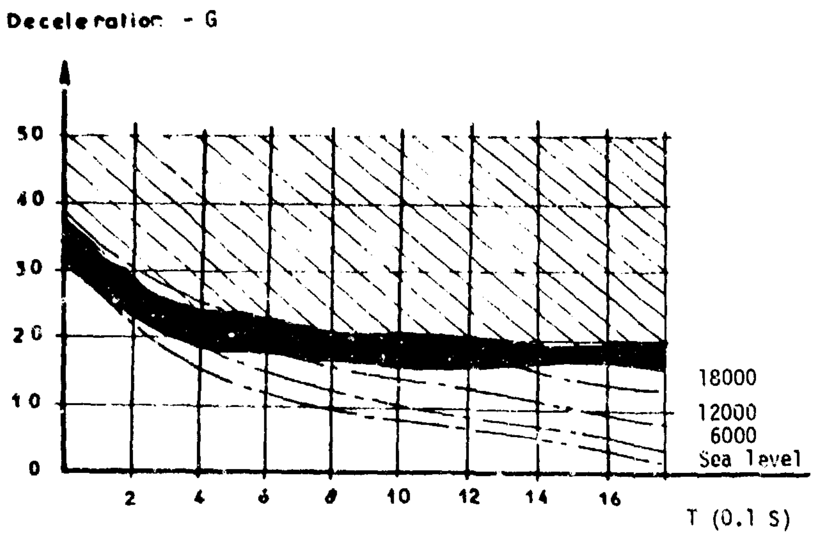
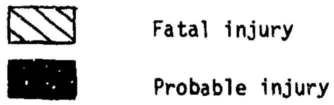


Figure 67. Rate of decay of decelerative forces with time.



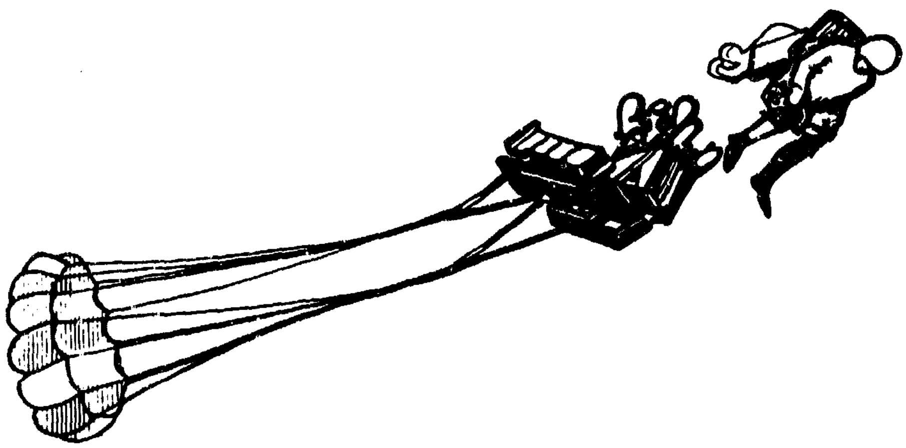


Figure 68. Man-seat separation (from U.S. publication).

2. Abnormal Configurations

The attitude of the aircraft can vary. Sometimes the ejection occurs with the aircraft inverted or heavily banked. Loss of control in rolls with high rates of rotation is not uncommon. The accelerations may be linear, radial or angular. In these configurations only the harness retains the pilot in his seat. There is a risk that the back will not be against the seat back and the weight of the pilot will not always be in contact with the seat cushion. For this reason the dynamics of ejection will be modified.

In a tight turn the acceleration generated by the manoeuvre is added to the acceleration of the seat. In spins in modern aircraft the -Gx acceleration developed by the rotation thrusts the pilot forward in his harness. Because the anchorage points of the harness are low down, the spine is placed in forward flexion. This change of the spinal geometry favours the occurrence of vertebral fractures when the seat begins to move.

All these considerations justify a repitition of what the posture of the pilot should be at the moment of initiating an ejection:

- The head is straight, with the back and buttocks firmly applied to the seat.

- The feet may remain on the rudder bar if the seat is fitted with leg restraints. Otherwise, it is absolutely essential to draw then back against the support.

- The position of the seat pan is not changed at the moment of ejection.

- Personal equipment, in particular the protective helmet, should be selected with the greatest care. Helmets that are too large tend to accentuate the curve of the upper thoracic column. What is more, they are easily displaced, and several studies from the NATO Air Forces show that loss of the helmet at any stage of ejection is an unfavourable factor carrying a greater risk of traumatic lesions of the skull.

Underwater ejections pose very different problems, as discussed by Davidson (46). They have not to our knowledge led to spinal fractures in surviving pilots of the French Naval Air Force.

3. Extraction (YANKEE System) (70)

Since 1966 the Stanley Company in the United States has evolved a system which does not provide "ejection" of the seat by the thrust from a gun later sustained by the combustion of the rocket under the seat, but "extraction" of the seat from the cockpit. In essence this YES system (Yankee Escape System) operates as follows:

After jettison of the canopy a pack of two rockets is pneumatically expelled upwards, drawing out a lanyard about 3 metres long, which is attached to the upper part of the pilot's harness. When this link is taut, the two rockets, which have divergent thrust, ignite and pull the "pilot-seat back" assembly upwards. The horizontal part of the seat pivots down so that the pilot leaves the cockpit in a "stretched out" posture (a pneumatic booster can also accelerate the upward movement of the seat). The thrust of the rockets assists the deployment of the main parachute by traction, even in cases of zero speed ejection or of abandonment in the direction of the ground. The acceleration experienced by the pilot is only of the order of 12 G, but the system does not seem, at the moment, to be practicable for ejection at high speeds.

The Yankee Escape System is widely used in many air forces.

5.3.3.5. Results of Ejections (9, 33, 35, 41, 67, 92, 93, 107, 127, 144, 176, 178, 191, 215, 224, 225, 226)

1. Overall Results

Any ejection that entails the death of the pilot may be regarded as a failed ejection. Among successful ejections, we include both those where the pilot in uninjured and those where slight or severe injuries are caused.

Two sets of statistics are available:

- One from the French Air Force, which comprises all the ejections from 1955 to 1979 inclusive, with non-automatic and totally automatic seats (Table 5.8) (50, 52, 73).

- One from NATO, comprising 678 ejections on modern automatic seats, in which a single initiating action (face blind, seat pan, armrest) triggers the automatic occurrence of all the events in the ejection sequence (Table 5.9) (9).

Despite the development of different techniques, the success rate has not increased in any appreciable fashion during the past ten years (Harrison, 127).

TABLE 5.8

Ejections in the French Air Force (1955-79 inclusive)
Non-automatic and automatic seats

Total Ejections	Unsuccessful (fatal)	Successful
429	93 (21.67%)	336 (78.33%)

TABLE 5.9

Statistics from Working Group (9) on Spinal Injury after Ejection Follow-up (Chairman: Gibert; Co-ordinators: Auffret & Delahaye) relating to ejections with automatic seats from the US Air Force, US Army, French Air Force, Royal Air Force, German Air Force, Italian Air Force, Hellenic Air Force

Total Ejections	Unsuccessful (fatal)	Successful
678	14 (16.81%)	564 (83.19%)

The number of deaths in peacetime operations remains high, even with fully automatic seats. The high speed conditions in which ejection seats are actually used causes very serious lesions often leading to the death of the pilot.

2. Results as a Function of In-flight Factors

Altitude

In ejections at low altitude and very high speed, the percentage of deaths is very high. The results are not greatly improved by the automatic operations of the various sequences. Spins at low altitude frequently compromise the success of an ejection. Similarly, at high speeds, the braking action of the seat stabilising parachute cannot always be adequately effective. It should be remembered that the ideal conditions for an ejection are an altitude of 15,000 feet (4569 metres) and a speed between 250 and 300 knots.

Speed

Most ejections take place at rectified air speeds of between 150 and 500 knots. Above 500 knots, the fatality rate exceeds 40%. The rectified speed is an aggravating factor and all the published statistics emphasise the increased incidence of lesions (particularly fractures) and of deaths with speed. High speeds diminish the chances of a safe ejection (37, 52, 94).

5.3.3.6. Distribution of Ejection Lesions

1. Spinal Fractures

These constitute the most frequent serious injuries and, despite all the recent progress in the technology of ejection seats, fractures of the spine remain, in the opinion of all specialists (engineers, doctors, test parachutists), the primary problem in ejection (9, 33, 35, 41, 52, 59, 69, 74, 85, 90, 91, 107, 111, 113, 124, 130, 134, 135, 136, 141, 144, 158, 164, 166, 183, 191, 195, 196, 197, 214, 215, 224, 225, 226, 237, 238).

Two sets of statistics are available (the one concerning all ejections in the French Air Force, the other from NATO).

TABLE 5.10

Number of Ejections	Pilots with Fractures	Total Number of Fractures
429	51	77 (French Air Force)
678	92	216 (NATO)

We shall examine in greater detail the NATO statistics, which comprise the results observed by seven air forces; US Air Force, US Army, French Air Force, German Air Force, Italian Air Force, Royal Hellenic Air Force, Royal Air Force. Thus, there is a total of 216 fractures occurring in 130 pilots ejected in automatic seats in recent years (Table 5.11).

TABLE 5.11

NATO Statistics (216 fractures)
1974 Working Group on Spinal Injury after Ejection (9)

VERTEBRA	NUMBER OF CASES
C1	1
C4	1
C5	3
C6	2
C7	1

VERTEBRA	NUMBER OF CASES
D3	4
D4	6
D5	13
D6	9
D7	11
D8	17
D9	10
D10	11
D11	16
D12	36

VERTEBRA	NUMBER OF CASES
L1	46
L2	11
L3	4
L4	5
L5	1
SACRUM	1
UNKNOWN	8

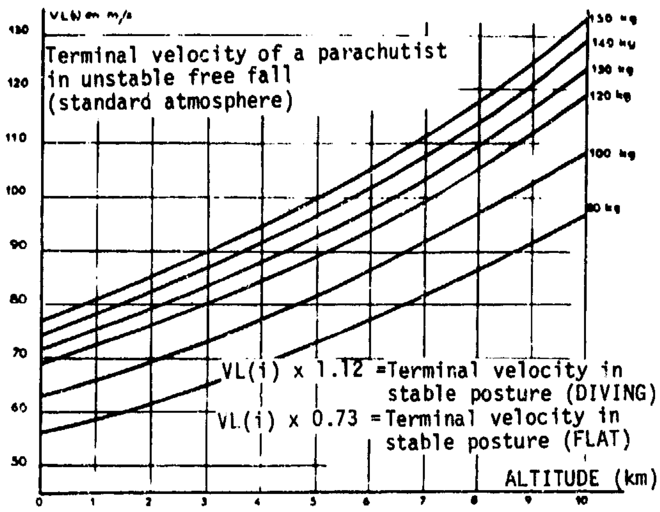


Figure 69. Terminal velocity of a parachutist in free fall, as a function of his weight and posture.

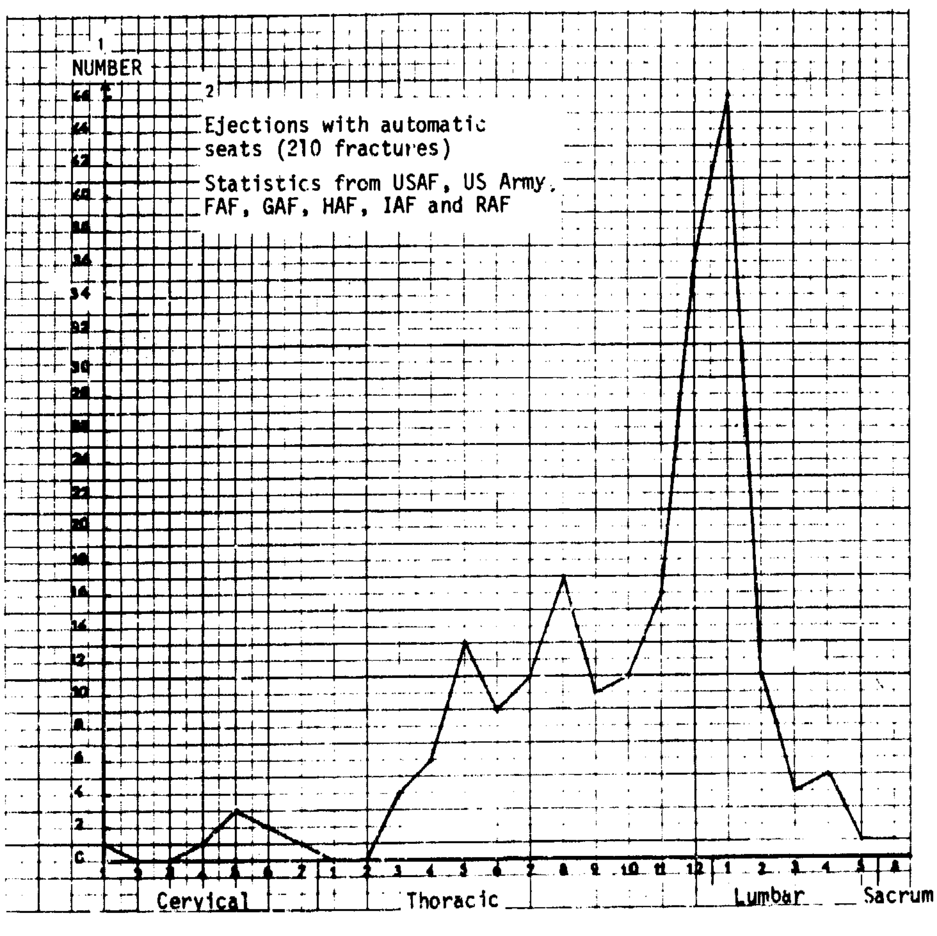


Figure 70. Statistics from the Working Group on Spinal Injury after Ejection.

The distribution (Fig. 70) shows that there is:

- a large peak at the level of D12-L1 (37% of cases)

- a high incidence of fractures of the thoracic column (more than half the total of spinal fractures after ejection).

These facts corroborate the data derived from examination of statistics relating to traumatic accidents in civil life (road accidents, accidents at work or in sports). In ejections it is difficult, not to say impossible, to state precisely the time of occurrence of a fracture of the spine; whether it was on firing of the seat, or on landing.

We may nevertheless compare two sets of statistics:

- Those from ejections in the armed forces of NATO, which include fractures arising both at the seat firing and on landing

- Those of fractures in French airborne troops, involving 1,181,155 jumps and 195 fractures (Fig. 71).

From a rough comparison of the two curves, it appears certain that the accelerations of the seat are likely to cause fractures over the whole range of the thorcic and lumbar spine. By contrast, in parachuting injuries, the fractures are predominant only at the level of the thoraco-lumbar junction.

Multiple fractures are frequently seen in pilots after ejection (40 pilots out of 92, or 40.8%). It must be noted that the presence of multiple fractures of the vertebral column is necessarily a grave matter (9). The dissipation of the energy has been spread over several fractures, which suffer less severe lesions than if there had been only one fractured vertebra. The distribution of multiple fractures shows that there is an infinite variety of combinations. It is difficult to confirm the existence of "preferred" associations, related to the anatomy and physiology of the spine, but we may note the frequent co-existence of:

- multiple thoracic injuries

- fractures of the region between D11 and L2 which may either be isolated or associated with injury at other sites.

We must also keep in mind the possibility of the occurrence of spinal fractures at different locations with the same type of seat, depending upon the type of aircraft and the operational role.

Other Lesions

Lesions other than spinal fractures primarily affect the lower limbs; fractures of the femur, the tibia, the fibula (lower 1/3rd), or the talus; dislocations of the hip and of the knee. Fractures of the sternum, ribs or skull (vault or base) rarely occur in isolation, and are seen in difficult landings. Loss of the protective helmet is always an unfavourable factor (67).

5.3.3.7. Pathogenetic Mechanisms of Spinal Fractures During Ejection (7, 9, 49, 52, 70, 73, 74)

Fractures of the spine occur primarily at two critical phases of ejection:

- initiation of seat movement

- landing.

The phases of man-seat separation and of opening of the parachute can cause injury in cases of malfunction.

1. Mechanisms During Seat Firing

All in-service ejection seats produce an initial acceleration compatible with the strength of the vertebrae; an acceleration with an amplitude of less than 20 G for 0.2 to 0.5 second, with a jolt that is in practice less than the normally accepted values (200 G per second).

A biomechanical model with a single degree of freedom is used by the USAF (Specification USAF-MIL A 9479) to determine the accelerations which a vertebral column can sustain. The dynamic response index (DRI) of this model is limited to 18 under standard conditions, which corresponds to a probability of vertebral injury of 0.05. Unfortunately, the model does not take account of poor positioning of the pilot or of the subsequent changes (which are difficult to quantify) in the distribution of forces acting on the spine which may be simple or complex in type (longitudinal, angular and radial). Moreover, the DRI applies only to the single Gz axis (+15°); it does not appear to us to have much practical interest, and we consider it to have little credibility in man. However, for the study of a seat in single axis, the procedure has some value.

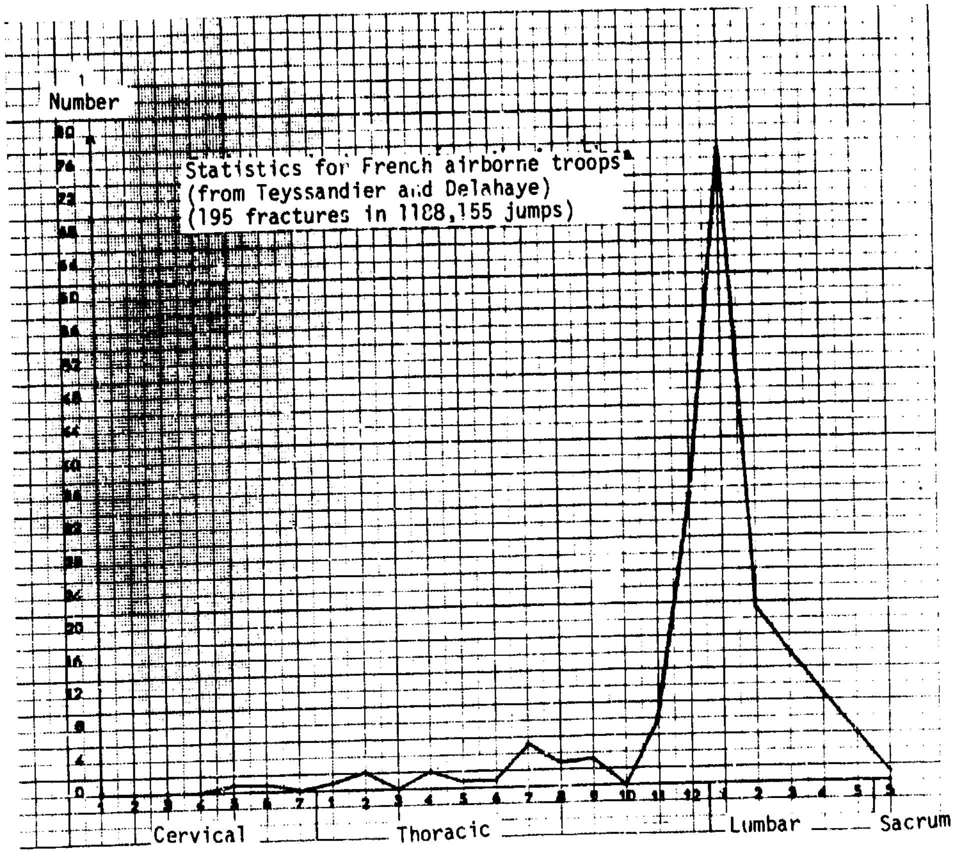


Figure 71. Statistics from French airborne troops (from Teyssandier and Delahaye, 240).

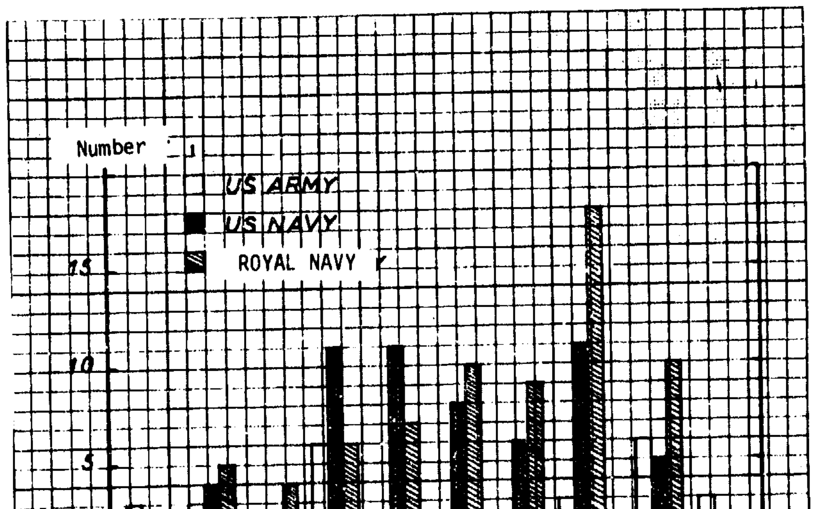


Figure 72. Spinal fractures with the same seat type (Mk J5) in different Services: US Army US Navy, Royal Navy (9).

The most important factor is the posture of the pilot at the moment of ejection (9, 13, 165, 197, 244).

Pilot Posture

We believe, with Rotondo (197) and very many other authors, that the position of the body is the most important pathogenetic factor in the mechanism of production of fractures of the spine. In the medical inquiry after an ejection it is important to make the pilot specify his exact posture at the moment of ejection.

Every abnormal position leads to relative weakness of the vertebral column and can give rise to lesions even when the accelerations would otherwise be tolerable.

The factors that modify the position of the pilot are very numerous. The attitude of the aircraft at the time of ejection is important, and it modifies the relationship between the seat and the pilot. Thus, in head-down ejections, the pelvis is necessarily separated from the seat, even if the harness is properly tightened. Similarly, in ejections from a steeply-banked aircraft, there is lateral flexion which is all the greater if the harness is poorly adjusted.

Restraint System

A very slack harness gives too great a freedom to the trunk, which bends considerably during ejection; there is a major risk to the spine.

On the other hand, over-tight adjustment sometimes explains the development of acute pain in the interscapular area, and the localisation of fractures in the upper thoracic region.

In the Martin Baker AM 4 seat, forward flexion of the trunk is limited by the face blind and by the restraint harness. With regard to seat-pan firing, Rotondo comments that flexion is more pronounced in tall subjects with a long thorax and shorter arms. In these conditions it is possible that the pilot cannot completely support his spine against the back of the seat within the very short time between the initiation and the ejection itself. Use of the seat-pan firing mechanism produces more fractures of the spine than initiation by the face blind (Rice and Ninnow: Report of the Working Group on Spinal Injury (9)) but these facts do not seem to be accepted by some authors.

The fractures occur at the curvatures of the spine:

- at the thoraco-lumbar junction

- most often, in the middle of zone D6, D7 and D8.

The vertebrae situated in the middle of these curves are weak points of the spine.

On the other hand, when the pilot is properly positioned (posture corresponding to the drills taught in training), the physiological curvatures are reduced. In fact, the lumbar lordosis and the thoracic kyphosis are decreased in the normal seated position. Thus, the column tends to become more straight, and this posture is optimal for tolerance of ejections.

Radiographic studies on ejection seats confirm the influence of certain factors on the flexion of the thoracic spine (23, 52, 53, 64). The adjustment of the seat is fundamental. A sitting position with the seat pan lowered tends to restore the lumbar "saddle" and to accentuate the thoracic kyphosis. If, in this case, the legs are drawn back against the ejection seat, the lumbar lordosis is corrected, but the thoracic kyphosis remains unchanged. There is then an angulation in the zone D4, D5 and D6. By contrast, in the normal position of the seat, bending the legs does not alter the curvature of the spine.

The height of the seat pan is adjusted to match the anthropometry of the subject. It must be appropriate to the height of the canopy (GAF) and be sufficient for the thighs to be supported by the seat and for the angle between the trunk and the thighs to be 135°.

There are no valid statistical relationships between anthropometric factors, weight, and lesions of the vertebral column (Kaplan, 142).

The influence of the dimensions of the pilot on the vertebral flexion during ejection has been especially studied by the US Army. In a radiological study, Kaplan found that for an ejection on the Mk 5 seat:

- in subjects with a short trunk (5th percentile of sitting height), the flexion and the risk of fracture at the level of L1 was increased

- in subjects with a long thorax (95th percentile of sitting height), the risk of vertebral damage at D8 was increased.

The US Army recommends a limitation of the height of the sitting subject between the 40th and the 70th percentile. However, the statistics from the US Navy and the US Army, for the same Mk 5 seat, show a very different distribution of vertebral fractures (Fig. 72). Similarly, the distribution of vertebral fractures in the statistics from the RAF and

French Air Force (Spinal Injury Group (9)), for the same Martin Baker Mk 4 seat, seems to prove that for two populations with relatively similar dimensions, anthropometric criteria alone cannot explain the localisation of the fracture. It appears probable that the correctness of the posture and the efficiency of the restraint play a part. Mohr (172) found that "there is no significant relationship between anthropometric measurements and vertebral alignment in the RF/F4C ejection seat".

Over-tensioning of the harness, especially if the anchorage points of the straps are situated low down, may increase the thoracic curvature, depending upon the anthropometry of the subject. Hurried adjustments, carried out just before the ejection, sometimes accentuate the flexion of the thoracic column and are the cause of compression fractures (Auffret, Seris and Delahaye, 1963 (53)). Some ejection seats are fitted with an automatic restraint system, which applies tension at the moment of ejection (power retraction unit). The advantage given by such systems is statistically significant in Mk 7 seats, and it reduces the risk of fractures (GAF). The merits of the system also appear to be evident in Mk 5 seats (US Army).

The posture of the head plays an important role. The head tends to flex forwards, because the muscles of the neck cannot always maintain it upright, even when the face blind is used. This forced flexion accentuates the flexion of the spine. Depending upon the physique of the subject (stature, torso length, relative thigh length) flexion occurs:

- at the level of the thoraco-lumbar junction (D11, D12, L1) in subjects of short or medium height

- at the level of D6, D7, D8 in tall subjects (in whom it may also be associated with the former).

The elimination of flexion of the trunk at the moment of ejection is the only way of removing the risk of spinal fractures (US Army). It seems that in the majority of ejections that actually occur, this precept is very difficult to follow.

This flexion is sometimes accompanied by rotation of the head, and these two movements produce complex accelerations at the level of the thoracic spine. Wearing a protective helmet that is too heavy, poorly fitting, or too bulky increases the risk of rotation of the upper thoracic column when the pilot's head is exposed to the windblast. An identical mechanism is encountered in ejections in a spine, and fully justifies the use of head restraint systems for special purposes (spin tests).

Any displacement of the centre of gravity of the head or too great an increase in weight exacerbates the forward flexion of the head and of the back, and increases the risk of spinal fracture.

Included Angle

The included angle is the angle between the axis of the spine and the line of thrust (Figs. 73 & 74). It deserves very particular attention. Large values favour the development of fractures of the vertebral column by hyperflexion. Even in the correct ejection posture, the spine is not aligned with the axis of the thrust. The included angle, when it is large, has the same effects as an exaggerated flexion of the trunk.

Diverse Factors

Serious anomalies of vertebral geometry, and especially of the thoracic kyphosis, must call for decisions concerning fitness for flight. Radiographs of kyphotic subjects, carried out on ejection seats, show that the sagittal curvature of the spine is little changed in the sitting position, even when the correct ejection drills are carried out. The frequent presence of thoracic scoliosis in young candidates for flying duties should make us consider, for the future, the effect of this disorder upon the risk to the spine during ejection (52, 53). In 1980, it is still too early to define precisely, for some very complex ejections, the relative statistical importance of these anomalies of the spine (scoliosis: accentuation or physiological thoracic kyphosis; combination of the two).

2. Abnormal Configurations

In many configurations (inverted flight, high angles of bank, spins) the back is not supported by the seat back, especially if the harness is not correctly adjusted. Moreover, the body mass of the pilot is not in close contact with the seat cushion. The dynamics of ejection are then greatly modified, and the acceleration amplitude (G factor) often exceeds the level of tolerance accepted by most air forces (25 G). Medical inquiries will try to determine the exact posture of the pilot, but they cannot assess the nature of the different types of acceleration and their importance. Experience unfortunately shows that ejections from abnormal configurations give rise to proportionately more vertebral lesions than those in which the aircraft is in normal flight.

Fig. 78 summarises various factors related to the pilot and the seat which cause vertebral trauma after the initiation of ejection.

3. <u>The Transmission of Accelerations to the Man-seat Assembly - The Importance of the Cushion</u>

Case History

The following very graphic example demonstrates the importance of a simple cushion.

While flying over a maritime region, a pilot was forced to abandon his aircraft because of engine failure. For this type of mission the rigid seat pack is replaced by a more flexible one with a folded dinghy on top. Furthermore, for reasons of personal comfort, this pilot had added a thick cushion of synthetic foam. The escape took place under ideal conditions; the pilot levelled the aircraft at an altitude of 2,000 metres and reduced the speed to 200 knots. He tightened his harness, meticulously checked his position and even found time to consult the ejection manual! At the moment of ejection he felt a very violent impact, and soon after became aware of a severe pain in his back. The parachute was caught in the branches of a tree. Radiographic examination revealed a fracture of the eighth thoracic vertebrae. In this particular case, the landing played no part. The ideal conditions of the ejection should not have led to injury. The spinal fracture was caused by the modified cushion, which adversely affected the transmission of force to the pilot so that the accelerations normally well below the limits of human tolerance exceeded the threshold.

Experimental Studies

These facts are supported by experimental results. Following the work of Latham (157) several authors measured accelerations in many series of experiments with dummies. Accelerometers were attached to the seats, and at different sites on anthropometric dummies (hips, shoulders, head). Several types of cushions were compared.

Analysis of the results showed that:

- the difference between the acceleration profiles at the seat and at the pelvis of the dummy varies depending upon the cushion used

- hard cushions give the best results, the curves recorded from the seat and from the pelvis being almost identical

- in general, the accelerations at the hips are higher than those at the seat

- in any given experiment, the accelerations increase progressively as the head is approached (Fig. 75).

Theoretical Mechanics of the Seat-Pilot Asembly (70, 73)

The simple mechanical equivalent of the ejected assembly can be represented by two separate masses connected by a spring-dashpot system corresponding to the elasticity and the damping of the cushion (Fig. 169).

If the spring is very stiff (or the damping is infinite) the accelerations recorded on the pilot and on the seat are the same. Any movement of the seat leads to an identical movement of the anthropometric dummy.

If the spring is less rigid, it is first compressed, and the acceleration is transmitted to the pilot after a lag. This delay corresponds to the relative displacement of the seat with respect to the subject. The movement is not transmitted until the spring is compressed beyond its point of equilibrium, and the energy stored by the spring in this first phase is added to that of the cartridge. On the recording, a transitory peak of acceleration is seen on the dummy. This greatly increased acceleration is achieved in a very short time; the rate of onset of the acceleration (jolt) is higher.

In fact, this very attractive model is too simple. The transmission of acceleration is modified by the dynamic properties of the spine itself.

The model developed by Dieckman (1957) (79), and taken up by Coerman (1962) (39) and his co-workers, explains the relationship between the initial excitation (acceleration of the seat) and its modification in traversing the human body (Fig. 168). Coerman considers that the body can be regarded as an assembly of suspended masses. Systems of springs and dampers (ligaments, muscles, intervertebral discs) tie the principal body masses together (head, thorax and arms, pelvis and legs).

The concept of resonant frequency is fundamental. It dominates the physiological effects of vibration and of accelerations on the human body. These effects depend on the applied frequency and the inherent frequency of each body segment. Resonance, that is, high amplitudes of displacement, will occur when the frequency of the forcing oscillations is equal to the natural frequency of the system (Chapter 6.1.).

The major resonance frequency of the vertebral column, the pelvis and the legs is about 5 Hz, and this must accordingly be filtered out to the maximum extent. However, elastic cushions have the property of amplifying a frequency of 5 Hz (0.2 second period) during the propulsive phase of many seats.

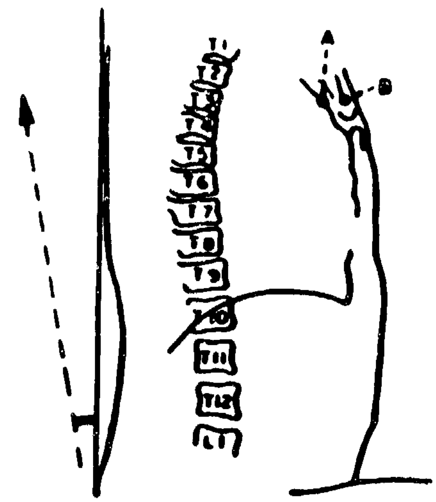


Figure 73. Tracing of radiogram of the trunk of a seated subject (from Latham, In Gillies, 106).
A. Centre of gravity of the body above D12 when operating the face blind.
B. Centre of gravity of the body above D12 when operating the seat pan firing handle.

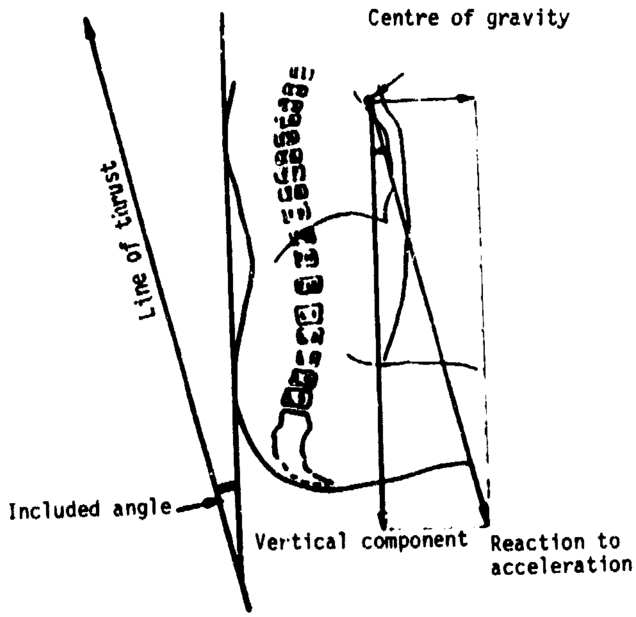


Figure 74. The included angle between the line of thrust and the spinal axis (from Gillies, 105).

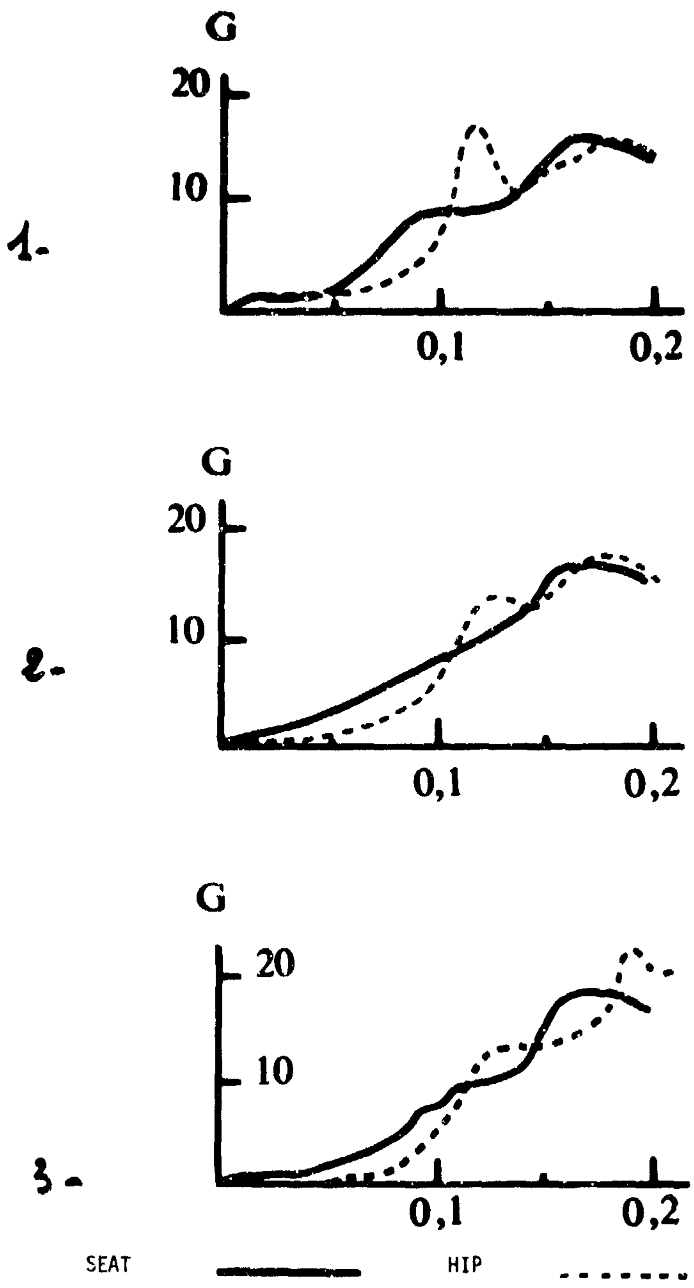


Figure 75. Acceleration profiles with different types of cushion (from Latham, 157).

1. Parachute, dinghy and water-containing cushion
2. Parachute and thin felt cushion.
3. Parachute and thick felt cushion.

———— Acceleration at the seat

- - - - - Acceleration at the hip

Seat cushions should be very rigid, and comfort is improved by increasing the area of contact (shaping the upper surface). The use of soft cushions is acceptable only with the express proviso that they are completely compressed under the weight of the pilot alone. It emerges from these studies that only homologous cushions which do not modify the oscillatory seat-pilot system should be used on seats.

In practice, these problems with cushions appear to have been mastered. In fact, survival packs are now enclosed in very rigid containers, usually of plastic. It is apparent that the limits defined for Gz accelerations (20 G for 0.1 second; jolt 200 G per second) represent maximum values for the pilot and not for the seat.

4. Through Canopy Ejection

In the case of escape either from an aircraft with a high rate of descent (vertical take-off aircraft) or over water (naval combat aircraft) escape through the canopy is recommended.

Two methods are then possible:

- egress through an intact canopy

- egress through a canopy previously weakened by a pyrotechnic cutting device.

Ejection Through the Intact Canopy

From an experimental study carried out at the Bretigny Flight Test Centre by Seris and Auffret (5, 206) from 1962 to 1964, using anthropometric dummies and cadavers instrumented with accelerometers, strain gauges and load cells, it was possible to derive much fundamental data.

In a normal ejection three new hazards arise:

- modification of the acceleration profile of the seat and of the dummy, probably causing greater accelerations at the level of the seat and of the body segments represented by the pelvis, the thorax, and the head. This produces greater compression of the vertebrae

- impact between the canopy and the head, the shoulders, and the knees

- tearing of the protective clothing and damage to survival equipment (life jacket, gloves, immersion suit, oxygen mask). Skin lesions of various depths may also be produced by fragments of plexiglass (perspex) which have pierced various layers of clothing.

With the aid of the experimental record from a through-canopy ejection carried out at the Aerospace Medicine Laboratory at Bretigny, we can study the sequence of events (Fig. 76).

At the onset, the acceleration of the seat is moderately high. It then decays rapidly (and may become negative) as one of the breakers comes into contact with the canopy and retards the movement of the seat. During this time, the acceleration measured at the pelvis progressively increases, and then changes its sign. The dummy continues on its upward path, despite the braking of the seat, as if it had parted company with the seat.

When the canopy breaks, the seat accelerates again, at first slowly during the disruption of the canopy, then more rapidly for a very short period when there is no longer an obstacle to its passage. Finally, the seat catches up with the dummy producing:

- deceleration of the seat

- secondary acceleration of the dummy.

Thereafter, the acceleration curves of the seat and the dummy follow almost parallel paths. The three records from the seat, the pelvis and the head exhibit oscillations which represent the exchange of energy between the seat, the cushion, and the various structural elements of the dummy.

Physiopathogenic Interpretation

The pilot is subjected to higher accelerations than those of a normal ejection.

When the canopy breaker contacts the canopy, the speed of the seat is low. The force that breaks the canopy requires a relatively high pressure in the gun tube. When disruption occurs, this pressure gives the seat greater impulsion, and this appears as a fairly high peak of acceleration. Moreover, when the seat movement is checked, the pilot continues on his trajectory and separates slightly from the cushion. The seat later catches up with him and he is projected upwards.

The recordings show that the jolt can reach 1000 G per second, but it lasts for only a few thousandths of a second. The accelerations are transmitted from the pelvis to the head in 0.03 second. If the duration of the peak is less than this while the head is being accelerated, the vertebral compression is smaller. For this reason, a peak of 40 G at the seat only produces 21 G at the pelvis and 38 G at the head, and the vertebral compression is moderate; 2250 Newtons. Conversely, for longer durations, all the shock absorption systems come up against the stops, and the vertebrae sustain a compression $F = m\gamma$. The peaks of acceleration are higher when the delay in penetrating the canopy is longer. The thickness of the canopy should be less than 9 mm.

Ejection Through a Weakened Canopy

This means of escape appears to be the best, and it also results in a gain of 1 second. The top of the seat reaches a canopy that offers no resistance and, accordingly, the acceleration profile produced by the cartridges is not changed. There is no significant impact to the head or to the knees. This method has also proved to be very effective in cases where the slope of the canopy is small, as in the F1.

Nevertheless, a fundamental point must be stressed. Weakening of the canopy can only be truly effective if the man-seat assembly does not encounter an environment of fragments of plexiglass. In fact, although high accelerations and impacts causing trauma to the knees and the head do not occur, the risk of damage to equipment and to protective clothing remains. Moreover, the danger of striking more or less large fragments of plexiglass in the slipstream is difficult to assess.

About 500 ejections through the canopy have been recorded throughout the world. The percentage of injuries observed in pilots, and especially of spinal fractures, is scarcely higher than for normal ejections.

5.3.3.8. Parachute Opening Shock (Fig. 77)

The time of deployment of the parachute is a function of the inflation of its canopy. The distance required for complete opening varies with the size of the parachute but is independent of the speed of travel.

It has been determined experimentally that a parachute must travel 6-8 times its diameter before being fully inflated. The filling time is inversely proportional to the rate of descent, and very high speeds involve very short inflation times.

The rate of descent will obviously be higher at altitude than nearer to the ground. At 20,000 metres the speed reaches 200 metres per second (400 knots), while near the ground it varies between 40 and 50 metres per second (100 knots) (Fig. 69).

At high altitude, the deceleration is greater and more rapid because of the increased speed of fall. The opening shock of the parachute is very abrupt, and the deceleration sometimes reaches 30 to 40 G. It can cause very severe damage to the parachute, and produce lesions of the cervical spine, either of the atlanto-occipital joint (183), or as fracture dislocations of C5 and C6.

In practice, these traumatic lesions occur only with failure of the mechanisms designed to prevent parachute opening at altitudes or speeds that are too great. They are exceptional.

5.3.3.9. Landing

Although there are considerable differences between the parachuting of an ejected pilot and of a military paratrooper, the pathology seen in the former is similar to the trauma suffered by parachutists. Many authors (see Shannon (215)) estimate the percentage of lesions attributable to landing as 30-40%. In medical inquiries after ejection it is, however, often difficult to determine the time of occurrence of a spinal fracture (seat-firing, landing).

At impact with the ground, the mechanism is two-fold; a vertical force from foot to head, acting upon a thoraco-lumbar column that is in hyperflexion. The fractures seen are variable in type, with or without injury to the discs and ligaments (see Chapter 5.3.4.). The primary localisation of these fractures is in the D12-L3 region, with an overall predominance at L1, and is identical to that encountered in other spinal injuries (aviation medicine, sport medicine, road traffic accidents).

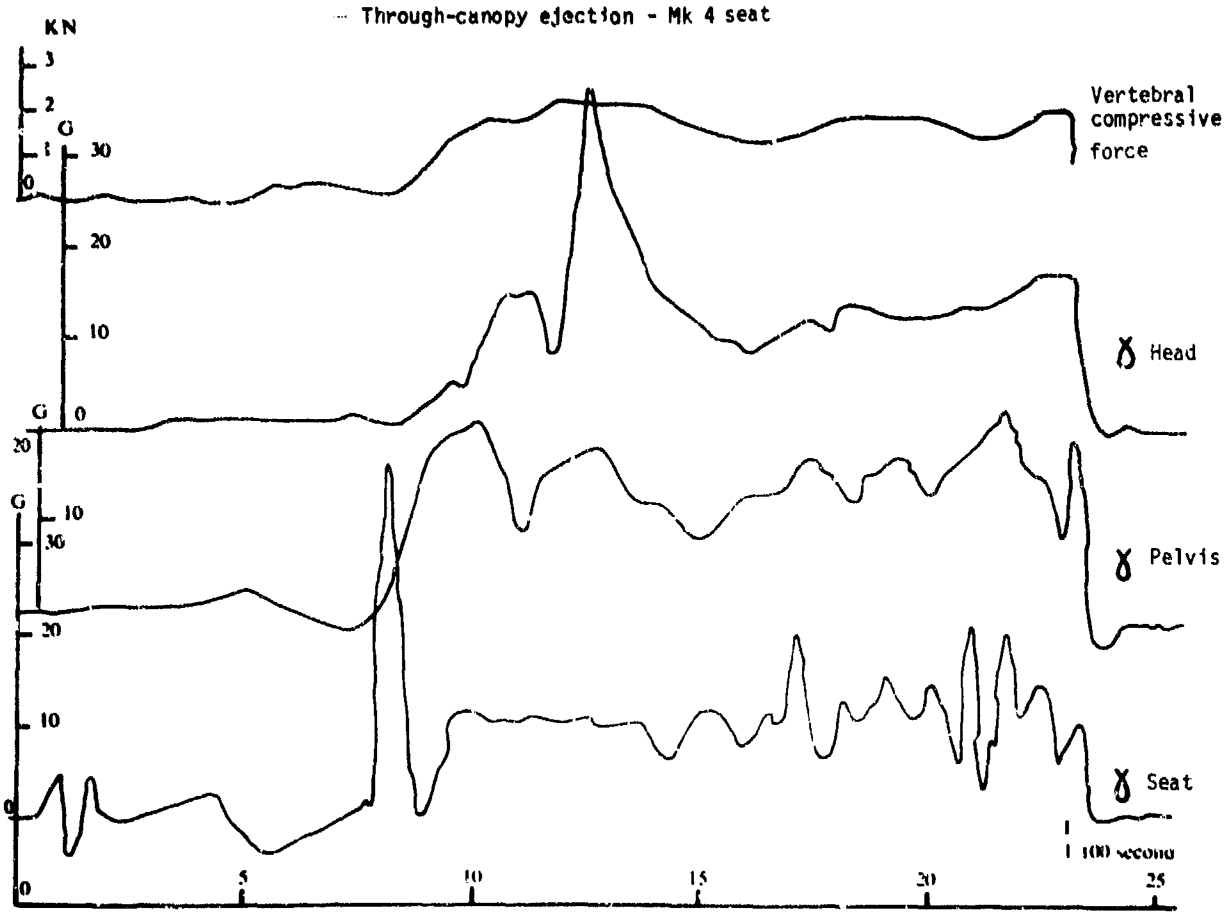


Figure 76. Through-canopy ejection - Mk 14 seat.
(Centre d'Essais en Vol de Bretigny-sur-Orge)

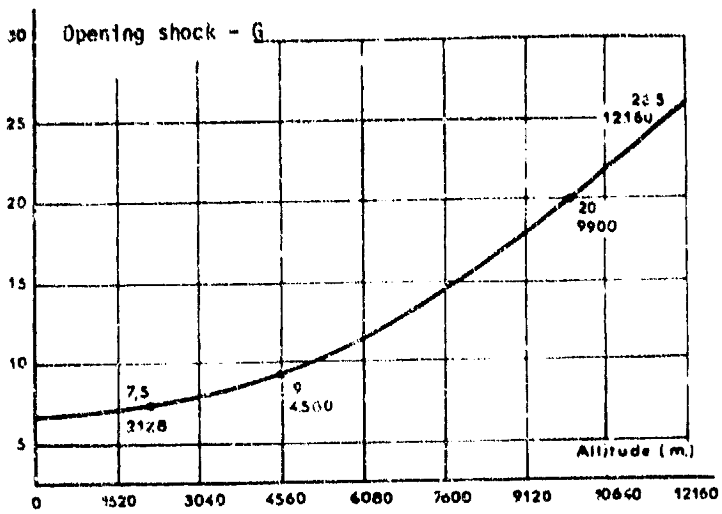


Figure 77. Magnitude of opening shock, as a function of altitude (28 foot canopy).

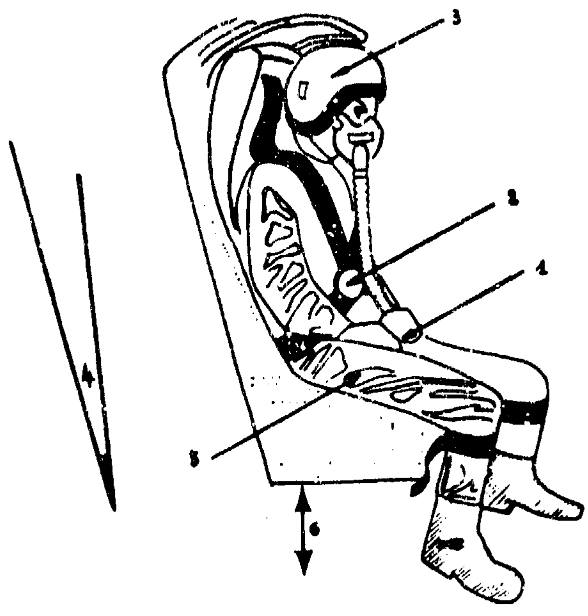


Figure 78. Diagram showing the different sources of injury caused by the seat or the pilot during seat firing.

1. Seat pan handle (with inadequate restraint).
2. Inadequate restraint.
3. Helmet too large.
4. Included angle.
5. Sitting position (extent of seat contact, and symmetry).
6. Height of seat pan (irrespective of G-force).

(from Delahaye et al)

5.3.4. Parachuting

A. Leger and R.P. Delahaye

SUMMARY

General Introduction

Originally employed as a means of escape by aviators and balloonists, the parachute has led, since 1935, to the evolution of new tactics for infiltrating behind enemy lines. In the last war (1939-45), parachute troops were used in commando actions in major operations; by the Wehrmacht in 1940 (Netherlands, Belgium), 1941 (Crete), and 1942 (Russia), and by Anglo-American troops (Normandy, Arnhem). By the end of the war, considerable progress had been made in the principles of use and in the techniques of training which foreshadowed the current scope of airborne troops. These have frequently been employed, especially by France, during campaigns in Indo-China and in Algeria, and by the Americans in Korea.

The need to reduce the risks of incapacitating trauma to a minimum led to the development of new landing techniques.

Sport parachuting was developed in France and throughout the world after the Second World War. In its early days, this sport was very similar to military parachuting, both in the equipment used and jumping techniques that were taught. The years from 1960 to 1980 saw a fantastic evolution in sport parachuting, which now has its own training methods and competitions, and which employs very special equipment (slotted parachutes, ram air canopies). To the basic techniques of precision landing and aerobatics has been added "relative work" which allows the grouping together in free fall flight of several parachutists to form patterns. Moreover, world championships are regularly held in these three disciplines.

Hang gliding is more like the flight of a glider, but the landing conditions are similar to those of a parachutist. Although there have yet been few operational military applications, we have decided to describe this new form of flight in which traumatic injuries are very common and often very grave. The free fall common to all forms of parachuting allows a study of impact, and we consider this aspect of biodynamics to be of interest.

5.3.4.1. Physiopathology and Aetiopathology of Parachute Descents

The experienced parachutist, the novice sportsman, the soldier - indeed, all parachutists whatever equipment they use - have a certain number of movements and of commands in common.

We may distinguish four periods:

- from leaving the aircraft to the opening of the parachute
- parachute opening
- descent on the deployed parachute
- landing.

5.3.4.1.1. From Leaving the Aircraft to Opening of the Parachute

1. The Exit and Its Problems (Fig. 79)

The Exit Proper

Leaving an aircraft in flight, at an altitude which may be high or low, generally appears to most people as an act contrary to nature. In fact, the effort that must be exerted before resolving to throw himself out of the aircraft proves to be very great for every novice parachutist.

It is exceptional for adverse incidents to occur at this phase of leaving the aircraft. The parachutist may strike the aircraft, or his parachute may hang up on some part of the structure.

Striking the Aircraft

There are two types of incident. The parachutist may come into contact with the aircraft fuselage. This sometimes causes loss of consciousness, the consequences of which will be dramatic if it affects a parachutist making a free fall jump without a barometric opening device.

When the subject is in position at the door, or is moving in the aircraft to reach it. the chest parachute may open prematurely. The canopy immediately opens in the slipstream and drags the parachutist out. Striking the walls of the aircraft is a serious eventuality which sometimes leads not only to injury to the parachutist himself, but also to damage of the aircraft.

Fouling of the parachute on the aircraft occurs as a result of defective functioning of the automatic opening mechanism of the parachute of a novice, or when there is premature opening of one or other of the canopies before the parachutist is sufficiently far away from the tail of the aircraft.

The problems of rescue are very difficult if it is not possible to unhook or retrieve the parachutist before the aircraft has to land.

Such incidents are very rare both in military and in civilian experience.

2. Free Fall

The incidence of trauma during free fall is currently very low. The main risk is from collisions in free fall.

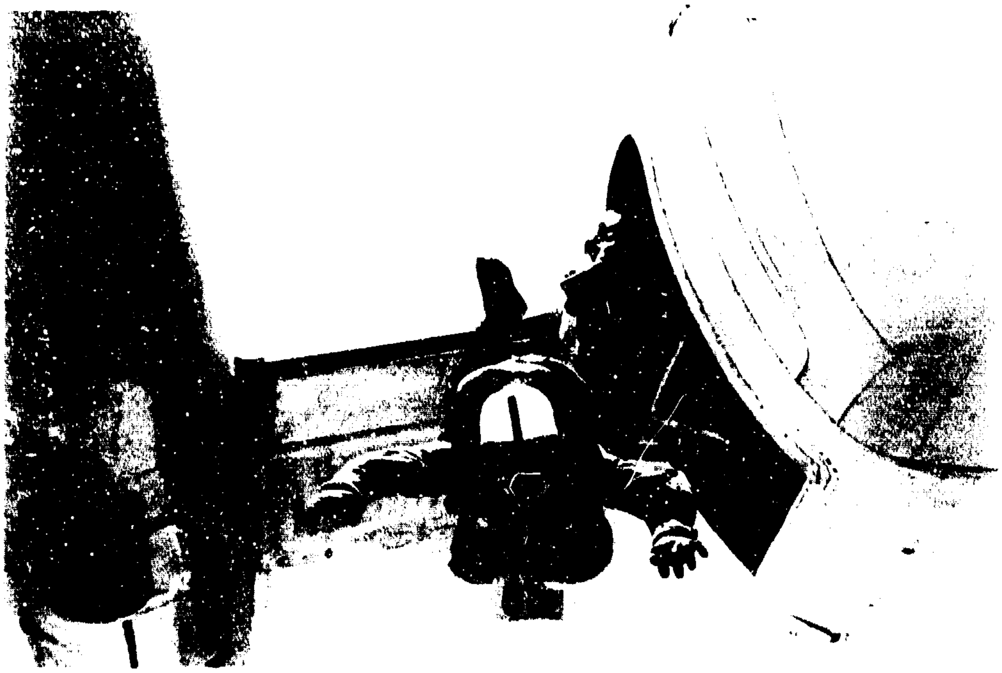


Figure 79. Experienced parachutist leaving heavy transport aircraft (Nord 2501).

Figure 80. Parachutist in position of maximum drive. The body is at an angle to the airstream, and the arms form an arrow with a negative dihedral. The velocity along the flight path can reach 220-230 km/h and the horizontal component can exceed 40 km/h.

Figure 81. Manual opening of parachute after free fall. The extractor parachute is beginning to pull the canopy from its pack, which was opened by the first action of the parachutist. Note the stable position, facing the ground.

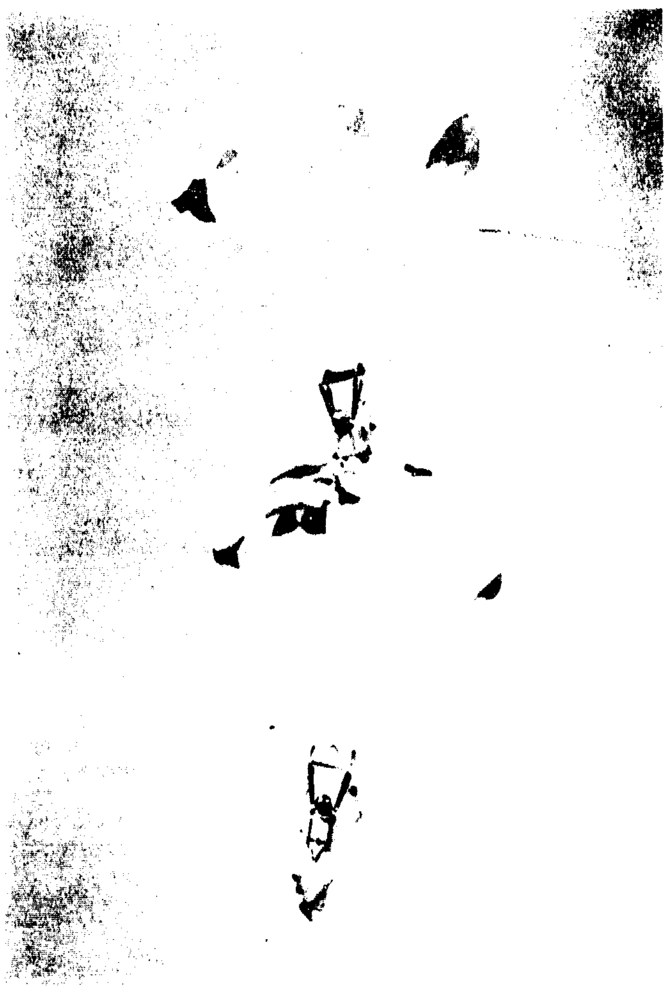


Figure 82. Canopy contact - Strato flyer parachute

In an attitude of maximum "drive" (Fig. 80), a parachutist has a high trajectory with a horizontal component of velocity close to 40 km/h. Nowadays, for different reasons, the techniques of civilian parachuting and those of operational airborne troops lead to the convergence of a larger and larger number of jumpers (12-15, or even more) towards the same point at the same time. Any collision between two parachutists during such manoeuvres can cause serious injuries.

A parachutist in free fall can also strike another whose canopy is deployed. This so far relatively infrequent occurrence sometimes produces grave injury, or even fatality.

5.3.4.1.2. Parachute Opening (Fig. 81)

1. Theoretical Aspects

The opening of the parachute constitutes the second phase. It takes about 2 seconds for the parachute to open completely. In this time, the parachutist travels approximately 80-150 metres, and his speed changes from 200 km/h to less than 30 km/h.

It is estimated that the opening forces to which the parachutist is exposed lie, depending upon the canopy, between 500 and 800 dN; a total force of 1200 dN is currently accepted as the maximum of tolerance.

The standard harness comprises three straps; the buttock strap and two thigh straps. The individual almost sits on the buttock strap, which is U-shaped and passes up each side of the body and in front of the shoulders. Each end is then attached to risers (two on the right and two on the left of the parachute) through which the opening shock transmitted by the shroud lines is evenly distributed. The two thigh loops arise from the buttock strap between the thighs and complete the closure of the harness in front. This harness was inspired by the requirements defined by J. Beyne in 1925:

- distribution of the opening shock over the largest possible area

- application of the sustained force to the parts with the best energy absorption (that is, to segments of the body padded with large muscle masses)

- localisation of shock points as far as possible from delicate organs

- support of the body in such a position that a correct landing is possible on reaching the ground.

The requirements of competitive jumping have, however, led to modification of the harness, to lighten it to the maximum extent.

The classical posture of a military parachutist during opening is similar to that of the foetus in utero:

- his back is rounded

- his head is hyperflexed, to bring the chin against the sternum

- his arms are bent and held against his chest

- his apposed legs are semi-flexed, so that the thighs make an obtuse angle with the rest of the body

- all his muscles are maximally contracted, particularly those of the back, of the neck, and of the abdomen.

In contrast, the free fall parachutist adopts, at the moment of opening, the most stable position possible; that is, with the body arched and the arms and legs extended as a cross (Fig. 86).

2. Practical Data and Physiopathological Incidents

The forces generated by parachute opening are large. Good postures which limit the risk of trauma are indispensable; the foetal position of the military parachutist, the stable cruciform posture of the jumper. These help to prevent the trapping of a limb by the canopy or the shroud lines during deployment.

Some modern canopies have opening characteristics incompatible with the supplementary loads carried out by operational parachutists. During operational tests of such parachutes, injuries of the cervical spine have occurred during opening.

5.3.4.1.3. Descent on the Deployed Parachute

For the novice, this is a time of calm and euphoria. There is a risk of entanglement between two parachutes which are too close together, and this eventuality often creates serious problems on landing.

Ram air canopies allow some experts to perform, during demonstrations, "canopy contact" manoeuvres which, in the event of an accident, frequently involve serious injuries (Fig. 82).

The largest proportion of traumatic injuries occurs on landing.

1. Landing

At the moment of landing, the parachutist, like any moving body, possesses energy which must be absorbed in a very brief time (half to one second).

The force required to dissipate this energy is inversely proportional to the braking distance. The energy which the parachute has is kinetic, of the form; $E = 1/2\ mV^2$. After landing, the velocity is zero and in consequence the kinetic energy is zero. The resistive work has the form $W = FL$. The following equations can thus be derived: $-FL = 1/2\ mV^2$ whence $F = mV^2/2L$.

This equation includes the mass of the parachutist, the speed at which he is moving and the stopping distance. In the velocity term, the component of wind speed plays a very important part. It can be shown by calculation that a parachutist using a parachute with no intrinsic speed and a constant vertical velocity of 6 m/sec receives an impact on reaching the ground of:

2.25 G for a wind speed of 0

3.25 G for a wind speed of 5 m/sec

3.5 G for a wind speed of 7 m/sec

5.5 G for a wind speed of 10 m/sec

This impact is represented by an acceleration vector coincident with the trajectory of the parachutist.

The physiological safety factor established by Bleriot (1905) is 5 times the weight of the body on the parachute. Accordingly, jumping will be prohibited if the wind speed at ground level exceeds 8 metres per second.

These dynamics factors explain the occurrence of severe injuries during landing in high winds (pilots in the terminal phase of an ejection, for example).

2. Landing Techniques

These play an important role in reducing the incidence of landing injuries.

It is estimated that a trained individual can absorb, through his legs alone, a force equivalent to two and a half times his body weight. Landing techniques aim to increase the stopping distance and to spread the effect of the forces over other parts of the body.

The recruitment of different muscle groups helps in the absorption of the forces generated on landing. The "roly-poly" technique has been developed for this purpose. To maintain a good position on landing requires a considerable effort of will.

For novices, the natural tendency is to shrink from contact as the ground approaches:

- by retraction (that is, by drawing the feet up under the body)

- by "searching" for the ground by a full extension of the legs.

In either case, the lower limbs cannot act as shock absorbers, and the spine will receive the greater part of the landing shock. The posture of the body on landing requires good symmetry in the sagittal plane for uniform distribution of the impact on both lower limbs (Fig. 84).

The two lower limbs should be semi-flexed and their muscles partially contracted, to make full use of the extended shock absorbers in the axes of the following joints:

- the ankles

- the lower legs

- the knees.

The position of the rest of the body is that which the military parachutist adopts at canopy opening, with muscles fully contracted.

This technique is not always scrupulously followed. The principal faults that lead to spinal trauma are:

- landing with the legs apart (the "stand-up" landing of experienced parachutists); the lumbar segment has to take the major part of the shock

- stiff back

- an erect head.

The seriousness of these errors in extreme situations, in heavy subjects or during landing in a high wind, can easily be understood.

In civil parachuting another technique is employed to avoid accidents. Because of the use of manoeuvrable parachutes with "drive" of their own, which are pushed to the limit of their performance, a prepared landing zone is imperative. Surfaces are chosen which have a high damping coefficient (washed gravel with a large coefficient of friction).

5.3.4.2. Parachuting as a Means of Transport

The traumatology of military parachuting is better known than that in the civil sector. Standard techniques, the centralisation and rigorous control of jumps, and the existence of accurate and accessible medical records form the basis for particularly profitable and serious study.

5.3.4.2.1. Equipment Used in Military Parachuting

The overall aim of the airborne forces is to accomplish the most rapid possible deployment of a large or small mobile force in a fixed area. Their use may be either as a "strike force" behind the enemy lines, in inaccessible or naturally-protected areas, or as reinforcements for a friendly unit that is more or less surrounded.

The parachute jump represents only a minor fraction of the total mission of airborne troops, but its requirements necessitate the use of suitable equipment.

Jumping equipment comprises several components; the parachutes (a main, back parachute and an emergency, chest parachute) and a jump suit. This equipment is used in training and qualifying jumps as well as in operations.

1. Parachutes

The main parachute (Fig. 83) employs an automatic opening device. The type currently in service in airborne units is the TAP 661-12, which was recently introduced as a replacement for the TAP 665 from which it differs principally by the absence of a metal frame in the pack. This modification considerably increases the comfort of the parachute and reduces its weight. The rigging is connected to the pack and to the harness by a D-ring with a removable pin. It consists of the canopy and the suspension cone.

The canopy is made of nylon and consists of 24 joined sections each divided into 5 panels. It has a hemispherical shape with an opening called the vent in its upper part. Its area is 60 m^2.

The rigging lines consist of 24 nylon cords with a strength of 2500 N divided into 4 groups of 6, and connected to the harness by 4 straps. These straps are called risers. With a load of 100 kg, this parachute provides a vertical landing speed of 6 metres per second. The only method of manoeuvre is to deform the canopy by pulling down on the risers.

The opening of this parachute is by the so-called "shroud first" system. The folded canopy is contained in a sack independent of the harness, in which the shroud lines are coiled. After leaving the aircraft an automatic opening strop (the static line), attached to the aircraft, causes the canopy to be extracted from its pack as the shroud lines uncoil. Once all the shroud lines are developed, the canopy leaves the pack. A tie thread with a strength of 550 N connects the vent of the parachute to the pack, and breaking of this thread allows the release of the canopy, which then opens completely. The total opening sequence lasts 2-3 seconds.

This method of opening has considerably increased safety, relegating the posture at exit from the aircraft to a place of secondary importance. Attempts are now being made to develop parachutes which allow the parachutist to be orientated face to the wind, while retaining some capability for avoiding obstacles.

The chest parachute is provided with a manual system of opening; it is connected to the main parachute harness by snap hooks and straps. The surface area of the canopy, which is always hemispherical in shape, is 45 m^2. The rigging lines comprise 20 shrouds.

2. Jump Suits

For the military parachutist these consist of a jumping overall, a metal helmet and a pair of "Ranger" high field boots. The kit weighs 7.5 kg. In manoeuvres or operations, the equipment container (13 kg), weapon, and ammunition, will have a total weight of 120 kg.

Most of the statistics used for the study of trauma in parachutists have been gathered at the Airborne Troop School at Pau. The majority of the jumps made each year are carried out with light equipment.

Special groups, carrying out free fall descents, use special parachutes, with more elaborate canopies.

5.3.4.2.2. The Techniques and Training of Military Parachutists

1. Teaching and Qualification in Military Parachuting

Preparatory training for parachute jumping is carried out at units or military training centres. Its purpose is to lead selected personnel through the various psychological and physical stages of the jump.

Psychological preparation is very important, as an extract from the "Regulations for Parachuting" shows; "the morale training of parachutists has the object of leading them to jump spontaneously."

"Esprit de corps, very strict discipline, pride in the uniform, the ability, competence and example of the officers; in a word, the general ambience of the environment which the officers can create, will be an excellent way of developing the spirit of daring which everybody possesses to various degrees."

Training for the jump itself is carried out in a parachute training centre. At present, only the Airborne School is authorised to give this training, apart from the Salon de Provence Air School which trains students under the direction of an instructing officer from the airborne forces. The training period lasts for a little more than 2 weeks full-time, the last week being devoted to 6 qualifying jumps, of which one is at night.

Psychological indoctrination and physical training aim to produce in the students the sequence of automatic responses which will be indispensable to them during a jump, from the exit to the landing. Study of the equipment, the exit from the aircraft, safety drills, techniques of landing (rolling from a standing position, or with the aid of special apparatus) follow one another throughout the entire period of training. The flight phase, leading to qualification, is at present carried out from Transall C160 aircraft with a capacity of 78-80 parachutists, and the release velocity is 130 knots (230 km/h). The jumping height is 400 metres.

2. Other Aspects of Military Parachuting

In training for static line jumps in various combat conditions, officers and non-commissioned officers are given exercises of increasing difficulty; jumps into wooded areas, into rough terrain, onto mountains etc. These various activities also include combat exercises and manoeuvres. There are also introductory courses to free fall, and training for instructor and operational jumpers.

5.3.4.2.3. Fracture and Trauma of the Spine

Trauma to the spine in military parachutists has been the object of many studies (4, 23, 29, 31, 52, 65, 71, 90, 98, 99, 101, 123, 148, 149, 159, 160, 190, 228, 230). It is the aspect of pathology which has received the most attention, while cardiovascular changes have received little.

1. Incidence and Distribution of Fractures

In the course of 1,330,000 jumps carried out at the Airborne Trooping School at Pau, 1,095 cases of spinal trauma have been observed, of which 159 were confirmed fractures (52, 193, 240, 241). The number of cases of spinal fracture, expressed as a proportion of the number of jumps, decreases each year (2.7 per 10,000 jumps in 1959, 0.5 per 10,000 jumps in 1966). This striking decline in spinal fractures is generally attributed to strict adherence to the parachuting regulations (weight limit of 80 kg, exclusion of all subjects with disorders of vertebral stability). The analytical study covering this period shows 159 cases of fracture involving 195 vertebrae (52, 240) (Table 5.12).

TABLE 5.12

Distribution of 195 Spinal Fractures (Airborne Trooping School)

VERTEBRA AFFECTED	NUMBER OF FRACTURES
C5	1
C6	1
C7	-
D1	1
D2	2
D3	-
D4	2
D5	1
D6	1
D7	5
D8	3
D9	3
D10	-
D11	8
D12	35
L1	77
L2	21
L3	16
L4	11
L5	6
S1	1

Multiple fractures are not infrequent (52, 240). In two cases, seven vertebrae were simultaneously affected (landing in very poor conditions) (Table 5.13).

It seems that the spinal segment most at risk lies between D12 and L3, this region being injured in 149 cases or 76%. Higher or lower sites are not exceptional. The cervical vertebrae are rarely injured. Damage to the posterior arch is unusual, but always very serious.

2. Pathogenic Mechanisms

Since the work of Greiffer (1939) all authors are in agreement that 90% of accidents caused by parachuting occur at landing.

To determine the curvatures of the spine of a fully equipped military parachutist at the times of canopy opening and of landing, Teyssandier and Delahaye (52, 240) obtained radiographs of the appropriate postures, which were checked by an instructor of the airborne forces. The opacity of the equipment and parachutes did not allow satisfactory antero-posterior films to be obtained, and only lateral views were used to make radiographic measurements.

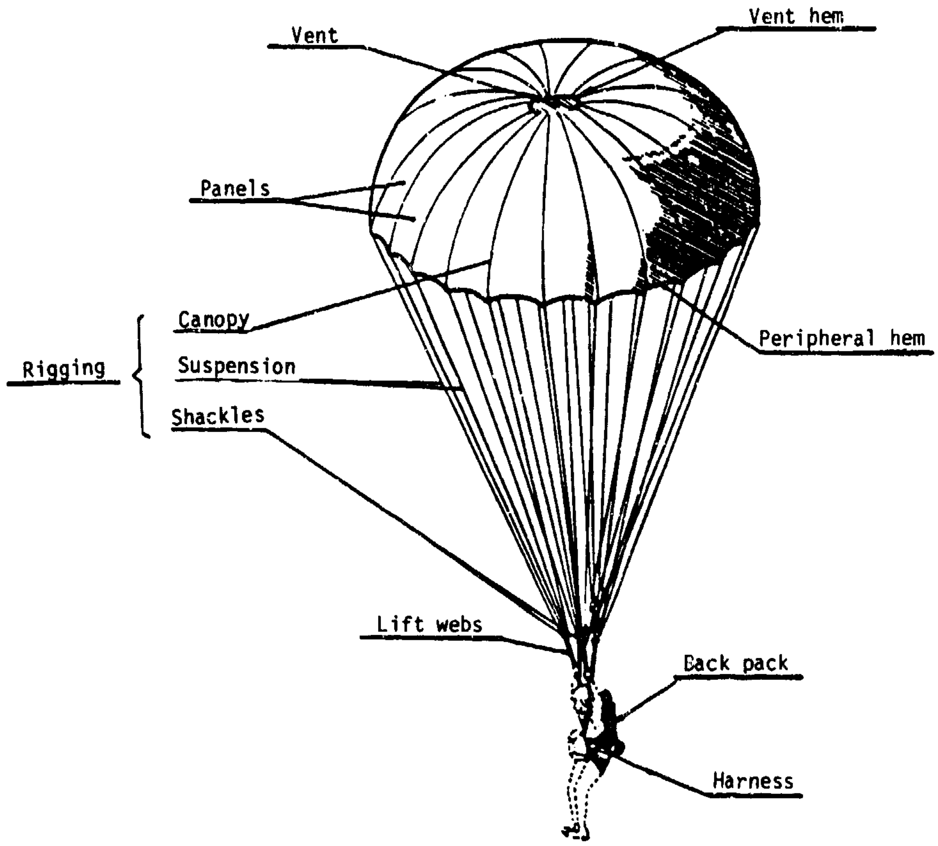


Figure 83. Diagram of automatic back parachute (from jumping regulations for French airborne troops).

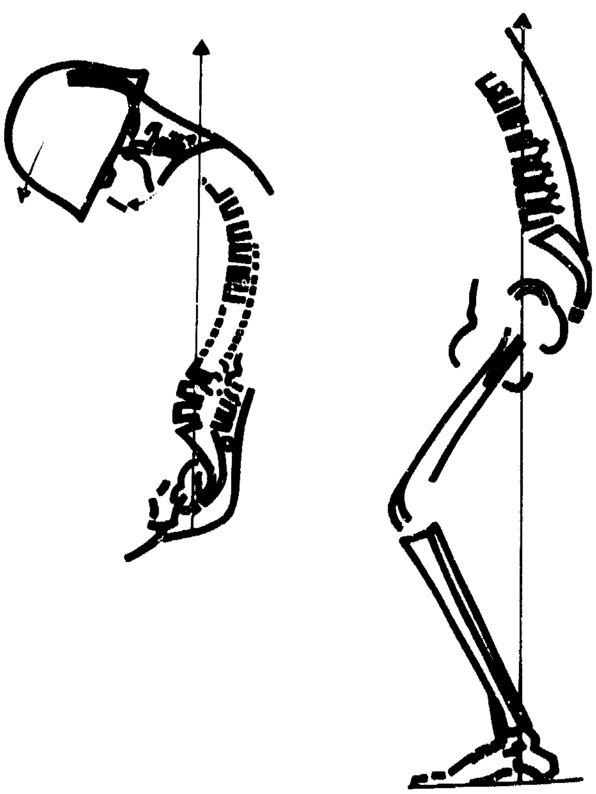


Figure 84. Tracings from radiograms of parachutists in the positions of:

a) opening

b) landing

showing the vectors.

TABLE 5.13

GROUPING OF FRACTURED VERTEBRAE	NUMBER OF CASES
D1 + D12	1
D6 + D7	1
D8 + D9	2
D11 + D12	1
D12 + L1	7
D11 + D12 + L1	3
D11 + D12 + L1 + L2 + L3	1
D11 + D12 + L1 + L2 + L3 + L4 + L5	2
D12 + L1 + L2	1
L1 + L2	1
L1 + L4	1
L1 + L2 + L3	3
L5 + S1	1
L3 + L4	4

Opening Shock

The opening shock of the canopy on the rigging lines for a parachute of the TAP 661 type can be represented by a vector (Fig. 84), directed from below upwards, the origin of which is at the lap belt and which has a value of the order of 225 kg for a subject weighing 75 kg. This vector lies in the frontal plane, and passes through the extremity of the coccyx, skirts the lumbosacral joint, and intersects the spine in the vicinity of the cervico-thoracic junction. This explains some injuries to the cervical column, which have become much less frequent since the system was modified to replace "canopy-first" packing by "canopy-first" opening.

Landing Shock

Landing shock can be represented by a vector (Fig. 84), directed from below upwards, the origin of which is the ground and the magnitude of which varies, for the same parachutist, with the square of the horizontal wind speed. This vector lies in the frontal plane and passes through the ankles and the hips, runs alongside the vertebral bodies from the 12th thoracic to the 3rd lumbar, and intersects the posterior wall of the spine at the level of the thoraco-lumbar junction. This explains the statistical finding that the spinal segment most at risk is situated between D12 and L3.

As for the mechanism of production of spinal fractures, they follow the rules cited by Watson-Jones and quoted earlier. The combination of hyperflexion of the spine with pressure acting on the vertebrae from below upwards is the usual mechanism. It leads to fractures of variable type and to disco-ligamentary lesions which most often lie at the level of D12/L2 (Fig. 85).

The cervical column can be damaged by an identical mechanism. The fulcrum of the level lies in the region of the cervico-thoracic junction. Flexion injuries can be caused:

- at opening of the canopy if the chin is not apposed to the sternum (which is extremely rare because of the state of intense muscular contraction)

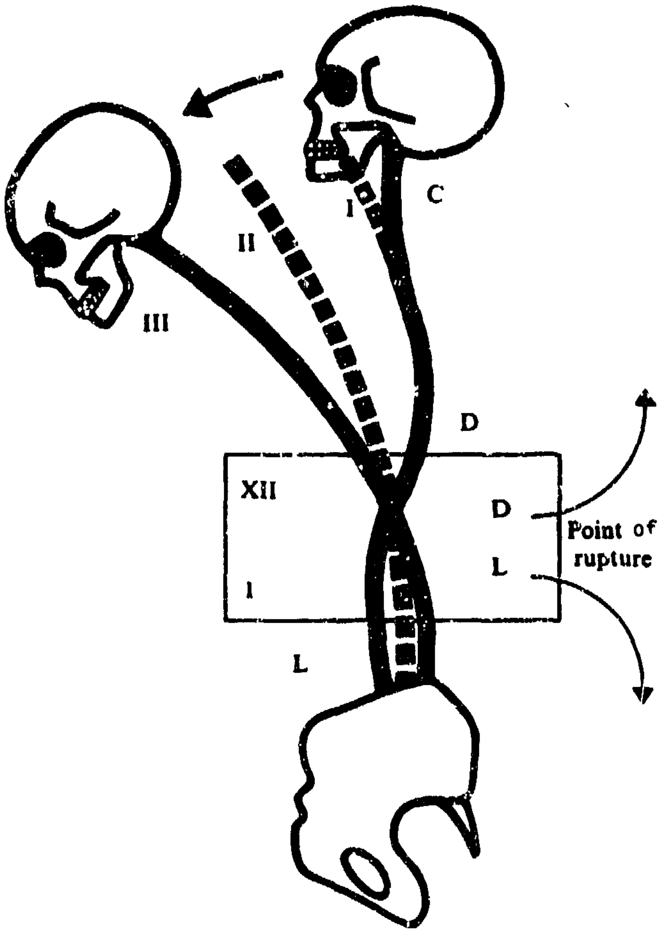


Figure 85. Straightening of the lumbar curve in forced forward flexion of the spine. Determination of the point of rupture, or junction point (from Forgue, 1903).

Figure 86. Parachutist in stable free fall. Note the cruciform position with arms and legs spread perfectly symmetrically.

- at opening, in qualified parachutists who are overconfident in themselves and in their equipment, and who do not sufficiently contract their neck muscles.

Hyperextension can cause cervical lesions. On landing, being thrown against obstacles sometimes leads to fractures of the spinous processes, to disco-ligamentary injury or to the rupture of blood vessels in the anterior anastomotic plexus of the medullary arteries.

Direct impact on the spine is the last mechanism to be considered. If a stone, or a branch, or any lump on the ground is in the area where the parachutist rolls at the end of the landing, direct impact sometimes causes lesions at variable sites which elude complete classification. A fall on the head can produce serious lesions of the atlas and the axis. This is a very rare accident of which one case has been reported by Hahn (123). After a bad landing (in training) in England during World War II, the skull acted like a hammer and split the atlas. Death followed in a quarter of an hour.

5.3.4.2.4. Other Lesions

The majority of lesions occur in the lower limbs (70% in the records of the Parachute School (65, 242)). They most frequently consist of sprains of the ankle, the knee, and the upper tibio-femoral articulation, fratures of the ankle (medial, lateral or posterior malleolus, alone or in combination), spiral fractures of the tibia, or fractures of the foot (tarsal and metatarsals); dislocations are more uncommon. Traumatic lesions of the upper limbs (fractures of the clavicle, dislocations of the shoulder, fractures of the scaphoid) or of the skull (vault, base) are exceptional. Injuries to the skull and upper limbs generally result from severe trauma (experienced parachutists jumping into mountainous regions, for example).

5.3.4.2.5. Traumatic Sequelae of Parachuting (52)

Microtraumata occur in the course of all jumps, even when they are normal, and it is difficult to determine their cumulative effects. It is necessary to differentiate them from the ordinary arthritic phenomena which occur in personnel who have sometimes had many years of service with the airborne forces.

Teyssandier (52, 239) has described the "vertebral syndrome of parachutists". It can appear at any age, after a delay which varies with the frequency and number of the jumps. Its clinical manifestation is pain, which appears in two distinct forms;

- the one chronic (most frequent)

- the other acute (more marked).

1. The acute pains appear first, generally superimposed on a background of chronic pain. They are usually triggered by physical exertion or, more often, by trauma. These pains, which are often localised, are sometimes accompanied by irradiations in the distribution of nerve-roots, either in a band or in a line. They appear most often at the level of the lower thoracic or lumbar column. Spasm of the paravertebral muscles leads to considerable functional impairment, and to the adoption of a pain-relieving posture (52).

2. Chronic pains are, according to Teyssandier, extremely common in parachutists. These sometimes diffuse pains are generally localised to a well-defined spinal segment. They are not usually accompanied by any irradiation.

Relieved by lying down and accentuated more by prolonged sitting than by standing, these pains increase towards the end of the day. Clinical examination reveals a more or less reduced mobility of the spine. The paravertebral muscle masses are hypotonic and may be atrophied. In more than half the cases (239), radiological examination shows the existence of a condition that pre-dates parachuting or is acquired (arthritis, sequelae of Scheuermann's disease).

The absence of radiological records before joining the airborne force does not make aetiological research any easier. Some acquired lesions (in particular arthritis) are in certain cases difficult to link with causative trauma. Long term studies, based on repeated clinical and radiological examinations, will perhaps help to define the consequences of professional parachuting experience.

5.3.4.3. Sport Parachuting

The Fédération Français de Parachutisme now has more that 9,500 qualified members. This sporting activity is not neglected in the military field, especially in the Air Force, which supports many aerial sports groups. Military athletes are, in fact, well represented in our national parachuting teams.

5.3.4.3.1. General Conditions of the Sport

1. Differences from Military Parachuting

The general conditions of sport parachuting (type of participants; equipment and techniques employed) differ considerably from military parachuting.

The philosophy of sport parachuting is fundamentally different from that of the military. For the latter, the parachute is a means of transport, designed to place a soldier and his equipment at a predetermined point to participate in combat action. He must exit from the aircraft and land on the required spot, while running the least possible risk in landing.

In the sporting context, preoccupation with leaving the aircraft is only a major factor during the initial training jumps. This thought is very quickly replaced by that of the "good jump".

The static line jump is only a brief stage in the career of the sport parachutist. The standard height for the jump is, in this case, 700 metres. The student must accomplish a minimum of 10 jumps with such automatic opening before proceeding, according to his aptitude, to manual opening. This term means that the opening of the parachute results from a voluntary action by the parachutist and not from an automatic sequence.

One of the aims to be met during static line jumps is the achievement of a stable position on leaving the aircraft, to ensure that the parachute opens in good condition. From the time that the parachutist is himself able to control the opening of his parachute, he passes to the study of free fall, with delayed opening of the parachute. This phase consists of mastering a stable body position in free fall. As a general rule the altitude of the jumps vary from 1,000 to 1,500 metres, and the time of free fall increases progressively from 3 to 20 seconds.

In the next stage, the parachutist rapidly progresses to an altitude of 2,000 metres and learns the elements of aerial manoeuvres; orientation, rotation, and translation. He is then considered capable of progressing to more complicated manoeuvres; rolls, loops, inverted fall, or even to perform the series of figures of competitive aerobatics. He may also turn his attention to the techniques of "relative" flight.

In parallel with the study of free fall, another concept is progressively developed. To the elementary notion of a safe landing is added that of a precision landing. It is obvious that this second element must never compromise the first, especially during the learning phase. Participation in competitions sometimes leads to an equivocal position in this respect.

On average, military parachutists only carry out a very small number of jumps within the strict military framework. Many sport parachutists are continually active, which leads them to make a large number of jumps in the course of a year. This is somewhat offset by the fact that a good number of initiates very quickly abandon the sport.

Finally, while the military population is very homogeneous, consisting of young men with a high standard of physical fitness, the sporting group is much less uniform with regard to age, sex, and physical condition.

2. Participants

It is currently accepted that any person enjoying a satisfactory state of health can, after a medical fitness examination, engage in sport parachuting. With regard to the spine, it is only practicable to carry out a clinical examination. Radiological examination is not obligatory, but is strongly recommended if there is the slightest doubt. The lower age limit is 17 years. There is no upper limit, and in this case the decision as to fitness is left to the good sense of the medical examiner. There is no limitation on weight, which need only be appropriate to the build. As to sex, the proportion of men to women may be roughly estimated as two thirds men and one third women.

5.3.4.3.2. Equipment Used in Sport Parachuting

In military practice, equipment is standardised. In sport prachuting, the heterogeneity of equipment is remarkable, and we shall only consider the different types of canopy in most frequent use at the present time. Sport parachutes can be categorised by the design of the canopy, which determines their potential performance.

Figure 87. Manoevrable hemispherical parachute EFA 65-20.

This is a training parachute with a slot in the intake, which gives the facility of rotation.

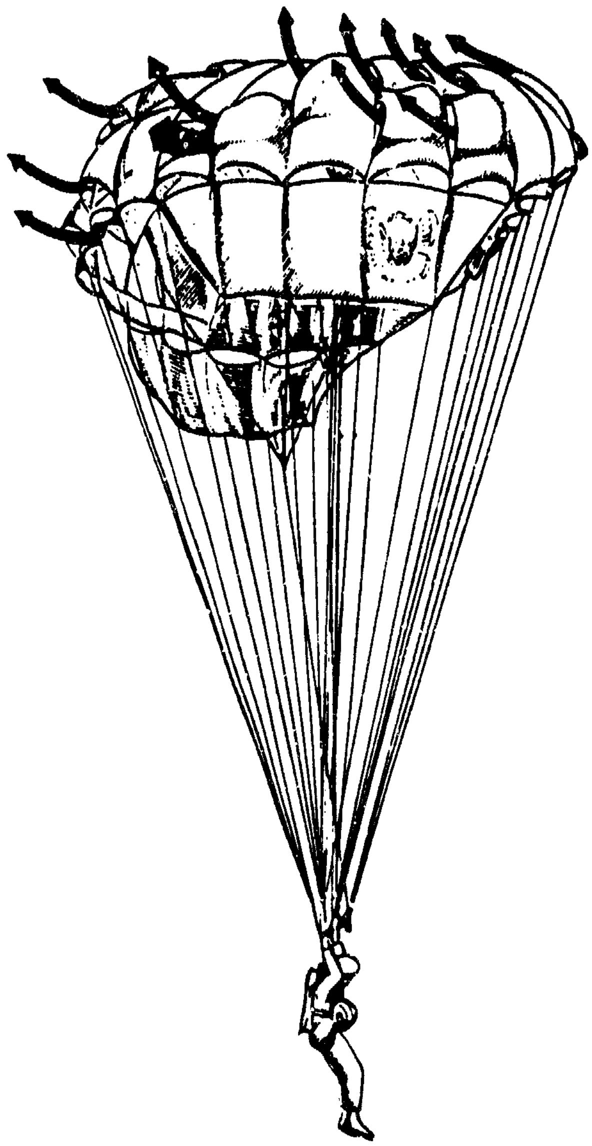


Figure 88. Olympic 657-11 parachute.

This has a so-called "nozzle" canopy (from the EFA flying manual).

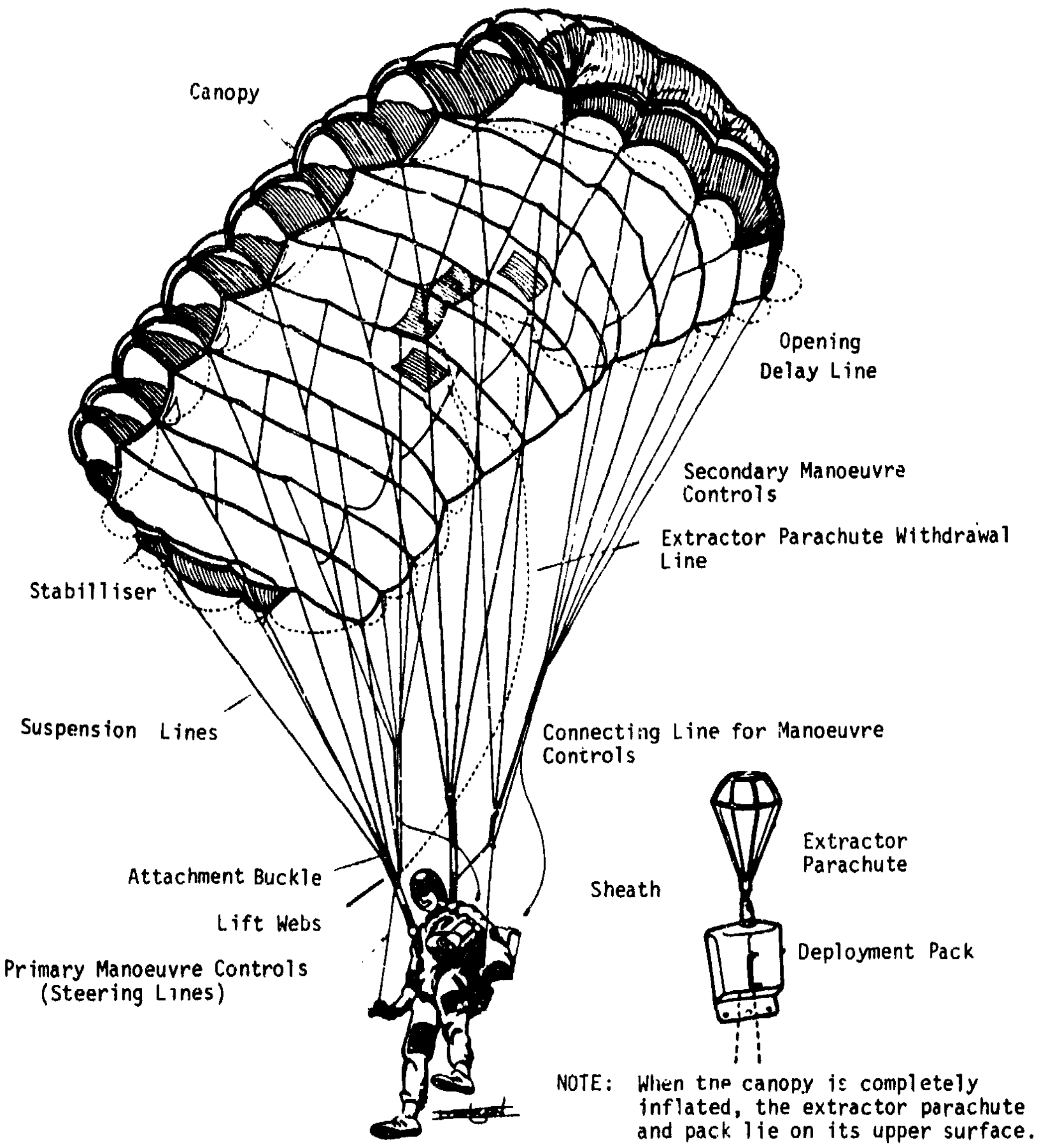


Figure 89. STRATO-CLOUD "parawing" parachute (from the EFA flying manual).

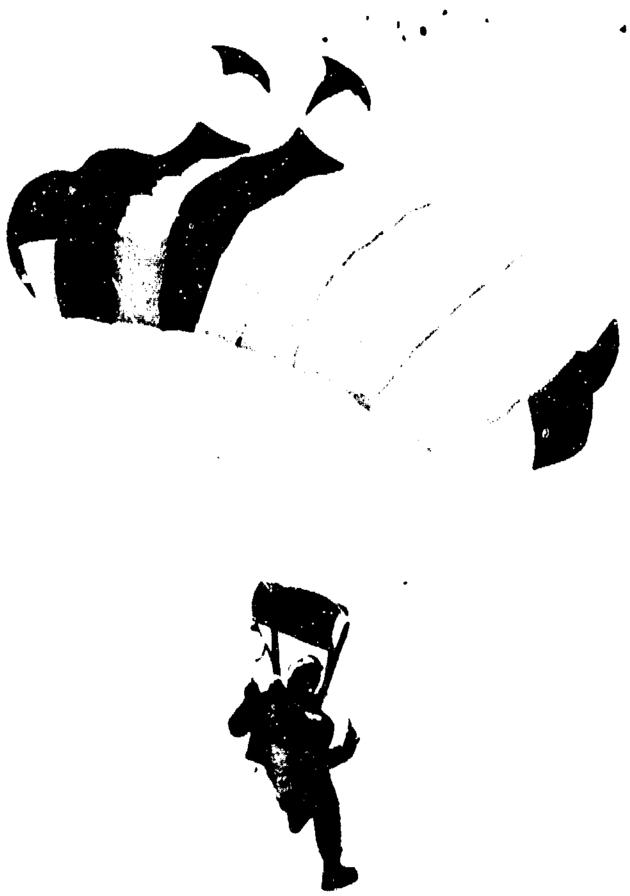


Figure 90. STRATO-FLIER "parawing" on final approach.
Note the reduced size of the canopy and the short length of the rigging lines.

1. Hemispherical Parachutes and Their Derivatives (Fig. 87)

These "novice" parachutes have canopies with the same characteristics as those of the airborne troops. To an increasing extent, training schools are using circular canopies with slots, which allow better orientation on landing, and permit certain manoeuvres to avoid obstacles.

2. Aerodynamic Canopies (Fig. 88)

Designed by the French engineer Lemoigne, these canopies were employed in competitions from 1964 until recent years. They are now obsolete for high level competitions, but are still used in advanced schools and for initiation to competitive jumping. Aerodynamic canopies give a maximum horizontal speed of 5-6 m/sec for a descent velocity of 5 m/sec with a 100 kg load. By appropriate manoeuvres effective braking can be achieved, leading to the cancellation and, to some degree, the reversal of forward speed. These canopies allow very good precision landings, but they have now been supplanted by parawings or ram air parachutes.

3. Ram Air Canopies (Figs. 89 & 90)

These canopies employ the same principles as an aircraft wing. They give great scope for manoeuvre. The glide ratio can exceed 2 or even 3 in the best cases. Such a ratio is very high for a parachute.

In the hands of a trained parachutist, this type of canopy is an excellent device for competition, allowing high-precision landings to be reliably achieved even in very difficult meteorological conditions. They have, in fact, considerably changed the face of precision landing competitions. However, like an aircraft wing, this type of canopy can stall; that is, lose all lift. This produces an immediate and considerable increase in the rate of descent. It is obvious that this configuration can be extremely dangerous, especially close to the ground.

On the other hand, used with full attention to safety (Fig. 91) this type of canopy allows very soft landings by cancelling almost completely the horizontal speed and the velocity of descent at the moment of contact, even in strong winds. With regard to the reliability of opening, considerable progress has been made compared with the first generation of such parachutes. Daily experience shows, however, that there is still an inherent risk in this design of canopy during opening.

5.3.4.3.3. Spinal Trauma in Sport Parachuting

The two activities - military parachuting and sport parachuting - are very different. Is the spinal trauma the same in both?

1. Data Collection

There is some difficulty in obtaining statistical data on trauma in sport parachuting. This problem is related to three factors:

- the wide dispersion of jumping sites
- the absence of local centres for medical care
- the lack of detailed reporting to a central organisation.

To participate in sport parachuting, insurance is obligatory, and Leger (159) has made use of the medical reports in the possession of the major company which insures parachutists. The analysis was made difficult by insufficiency of detail in the diagnostic records. The site of the lesion is sometimes the only identifiable fact.

2. Results

From 1968 to 1974 inclusive, 214 spinal injuries were recorded. This represents 9.3% of the trauma occurring in sport parachuting. Table 5.14 shows the distribution of fractures and spinal injuries.

It is of interest to compare these results with those observed in military parachuting (Table 5.15).

Although the number of jumps appears to be little different (1,100,000 in sport parachuting; 1,330,000 in military parachuting), the number of vertebral lesions is much smaller in the former (a ratio of 4.5:1). In contrast, the number of fractures is much higher in sport parachuting (57 out of 214 spinal injuries, or 26.64% compared with 16.7% in military parachuting). It is probable that many minor injuries to the vertebral column are not recorded, and that fractures are missed for want of radiological control. In sport parachuting there are many sacro-coccygeal injuries, more frequently in women.

TABLE 5.14

(From Leger (159))

	TOTAL	MEN	WOMEN
Vertebral fractures	57	39	18
Spinal trauma without fracture	95	76	19
Injury to sacrum and coccyx	62	26	36
TOTALS	214	141	73

TABLE 5.15

Comparison of Trauma in Military and Sport Parachuting

(1) From Delahaye & Teyssandier (52) - 1959-1966 inclusive
(2) From Leger (159) - 1968-1974

	Military Parachuting (1)	Sport Parachuting (2)
% trauma in relation to number of descents	8.3	9.3
Total accidents	11,533	1,315
Spinal injury (including fractures)	957	214
Vertebral fracture	155	57

The distribution of fractures has no particular characteristics; the primary locations are at the level of D10, D11, L1 and L2, with a higher incidence at L1, few injuries to the posterior wall, and a low incidence of neurological complications. The fractures occur on landing or during collision in free fall.

5.3.4.3.4. "Relative Work" (Figs. 92 & 93)

"Relative work" is the term applied to the activities of free fall parachutists, with the object of moving relative to one another until physical contact is established between 2 or more of them. This work can be extended by the execution of a series of aerobatics carried out as a group, in accordance with a pre-determined sequence.

This type of activity has been practised by some experienced parachutists since the early days of sport parachuting. It has developed greatly in the past 10 years, mainly by the initiative of American jumpers.

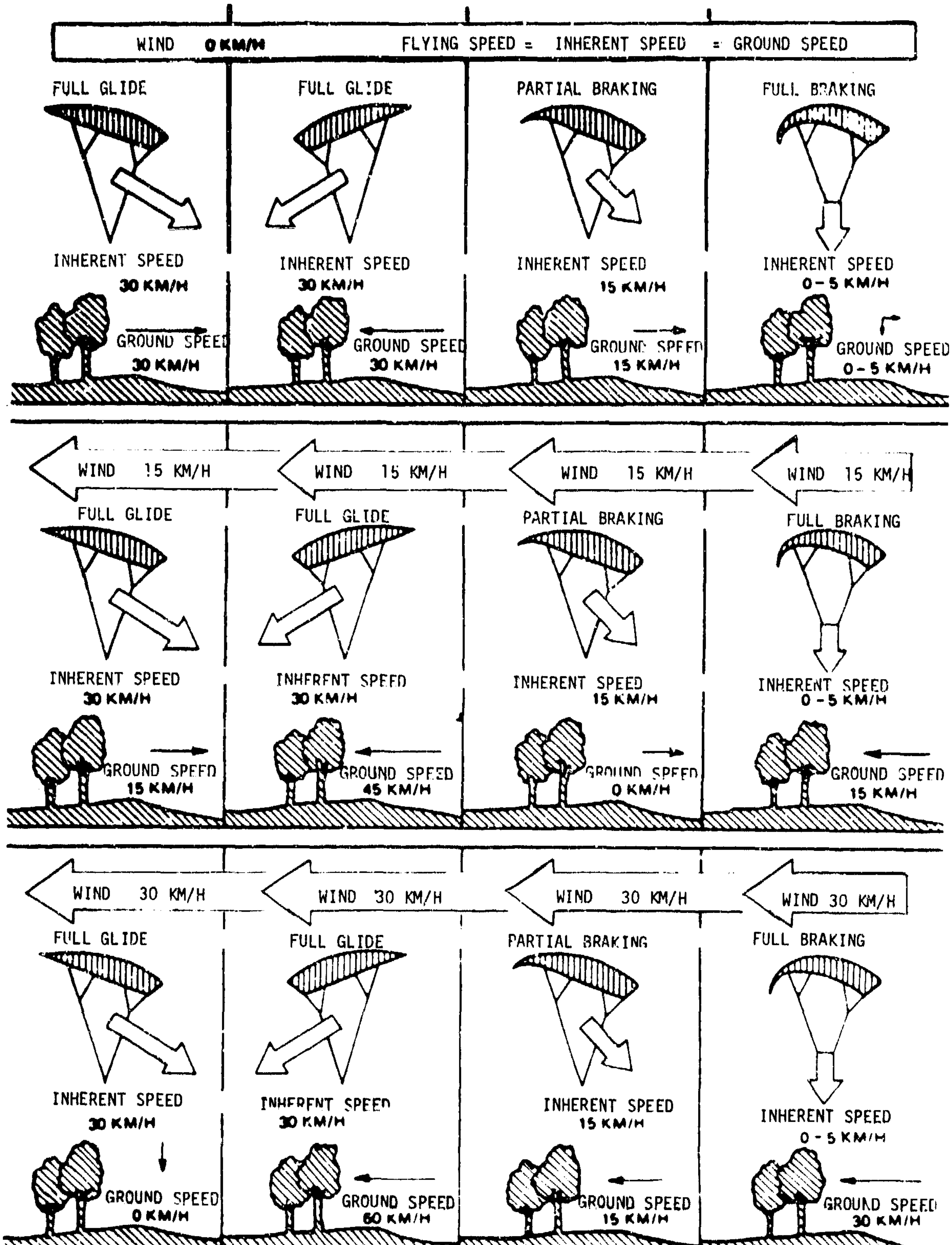


Figure 91. Capability and performance of a "parawing" parachute.
(taken from the EFA Stratocloud flight manual)

Figure 92. Relative flight: formation of a star of six.
Note the 2 parachutists on the right approaching the group of four.

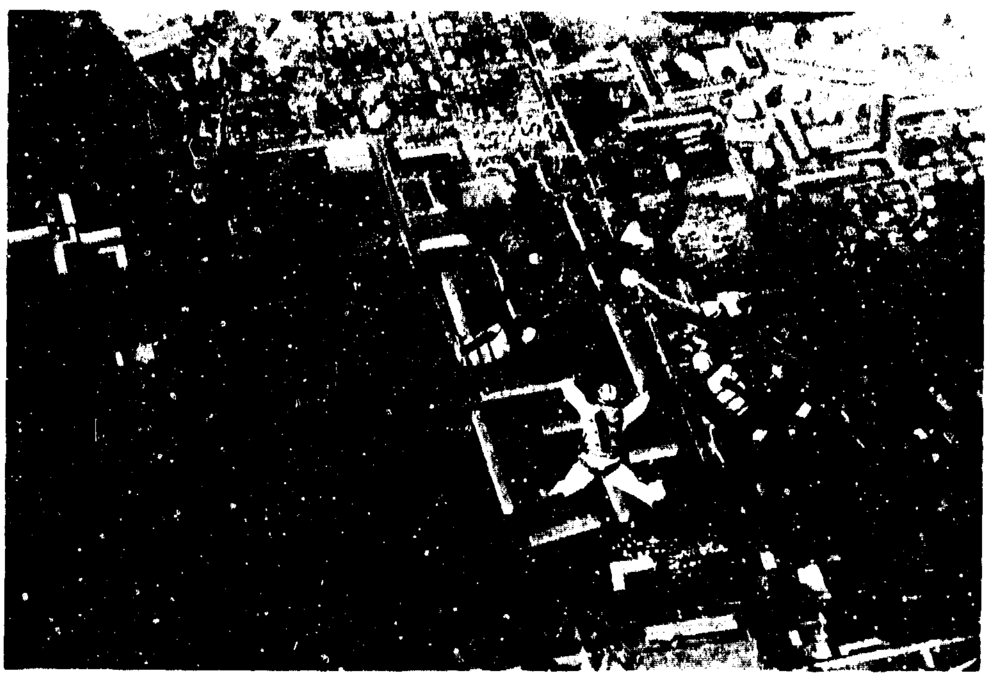


Figure 93. Six in star formation.

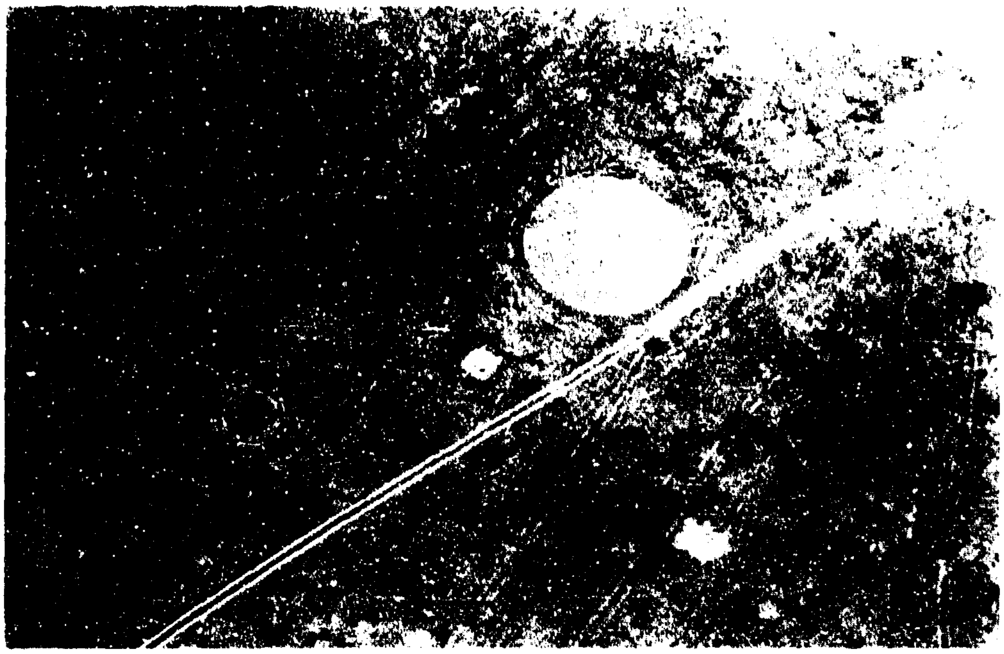


Figure 94. Precision landing.

Target set out for precision landing.
An Olympic-type parachute is approaching it.

Figure 95. Precision landing.
Olympic-type canopy.
Note the landing posture, with the right leg fully extended, trying to reach the central spot, and the body almost out of the harness.

Very roughly, the technique has two aspects; to regulate the vertical speed of descent by changing the surface exposed to the airstream (varying the drag), and to create lift by adjusting the attitude of limbs or their segments, so allowing translational motion. The combination of these two fundamental elements requires accurate judgement, especially in the critical moments of approach to another parachutist or to a group (Fig. 92).

The risk of collision is present in all phases of flight:

- after leaving the aircraft when the parachutist tries to catch up very rapidly with those ahead of him

- during the approach if the speed along the trajectory is inadequately controlled

- at the time of separation, when each jumper is occupied in moving away in search of his opening point.

In practice, relative work is really no more dangerous than the other aspects of parachuting; at least, as shown by the record of recent years. To remain safe, the discipline always requires a proven personal technique and strict observation of the safety rules.

With regard to spinal injury, collisions in flight can give rise to serious lesions. In this field, everything depends on the part of the body which strikes and that which is struck, as well as on the relative speeds of the parachutists.

The thoracic and lumbar regions of the spine are relatively well protected by the parachute pack. In contrast, the cervical column is much more exposed.

However, it must be noted that in 12 cases of collision in flight resulting in injury, Ravalec (190) did not observe any spinal fractures. He noted the existence of several cases of "cranio-cervical trauma". On the other hand, at the Begin and Dominique Larrey Hospitals, we have followed 4 fractures since 1978; one fracture of the seventh cervical vertebra, one of the spinous processes of C6/C7, one of the transverse processes of L3/L4, of the sacrum and of the pelvis (collision in flight), and one fracture of L3/L4 (transverse processes).

In another context, the occurrence of a severe cervical lesion during descent has every chance of a fatal outcome in the absence of a barometric opening mechanism or in very special circumstances (opening shock of the parachute).

5.3.4.3.5. Precision Landing

The performance of precision landings in the competitions that are peculiar to sport parachuting is a source of a certain number of spinal lesions.

In essence, the objective is no longer to make the safest possible landing, but to alight on a given point, with the greatest possible precision. This type of exercise is carried out onto a prepared target, generally of small gravel. The optimum point of touchdown is marked by a round spot 10 cm in diameter (Fig. 94).

The parachutist who manages to land with one foot on the spot is awarded the highest precision (0 metres, 0.0), or "square" in parachutist's jargon. Several attempts are generally allowed. For each jump, the precision is measured by the distance between the edge of the central spot and the first point of impact of the competitor. Experienced parachutists quickly learn to reduce this distance to a minimum by stretching a leg towards the target, or by throwing the whole body sideways during the landing (Fig. 95).

Taking into account the fact that the parachutist most often hits the surface tangentially, these manoeuvres are not actually very dangerous. Sometimes, when the vertical speed is higher, the relative absence of shock absorption by the lower limbs, and the forces of landing, may result in spinal trauma (Fig. 96). A sudden increase in the rate of descent of the parachute can be due to a faulty manoeuvre (stalling at ground level) or to an over-abrupt approach manoeuvre (rapid rotation etc.). Thus, fractures of the spine are not infrequently observed in competitions or in training, where parachutists have pushed their competitive spirit to the limit.

In relative work and in trials involving precision landings, the importance attached to the spine in parachuting trauma does not rest on any quantitative basis. Injuries of the spine are, in fact, a long way behind those of the lower limbs. On the other hand, the acute or long term consequences of spinal trauma should stimulate maximum effort toward their prevention.

Figure 96. Precision landing. Short approach with the whole body thrown forwards, support being achieved by traction on the rear lift webs.

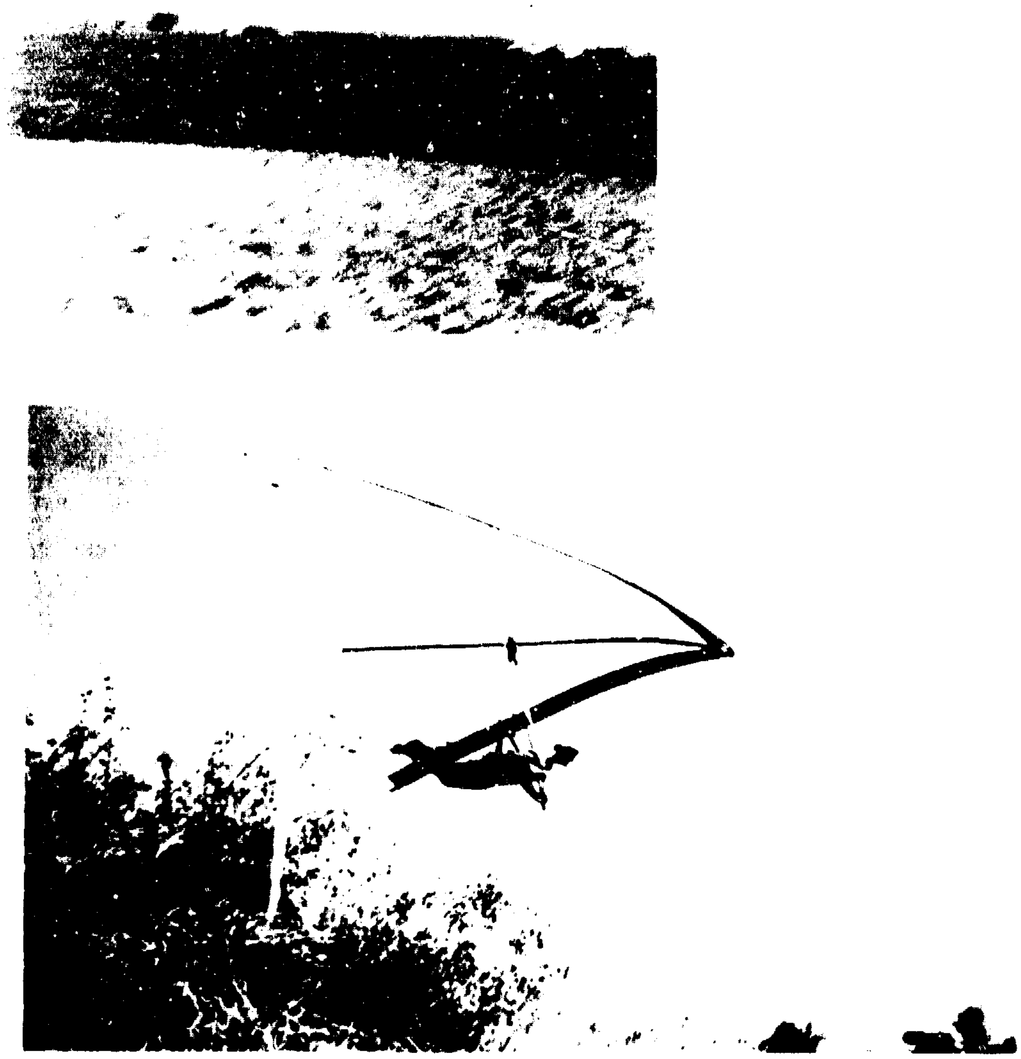


Figure 97. Hang gliding - Launch of a Delta plane.

5.3.4.4. <u>Hang Gliding</u> (Fig. 97)

Hang gliding is a new field which represents a sort of intermediary between gliding and parachuting. In its piloting techniques and the equipment used, the hang glider is undoubtedly closer to the glider. On the other hand, a hang gliding enthusiast shares with the parachutist a total absence of protection in case of crash or collision.

The possibility of spinal injury exists at take-off with the serous risk of "hitting the wall", but arises principally during faulty landing manoeuvres (stalls, poor weather conditions). In serious cases it involves multiple trauma not specific to this sporting activity.

The ill-resolved problems of regulations and of training associated with this new discipline partly explain the high morbidity that is observed: frequent fatalities and serious injuries, notably trauma to the thorax, to the lower limbs and to the spine.

5.3.4.5. Limits of Human Tolerance for Impacts in Free Fall

SUMMARY

5.3.4.5.1. Definition

"A free fall may be defined as any unimpeded fall, jump, or dive from a known point to a known impaction point." This definition, taken from Snyder (230), excludes falls down stairs and jumps from cliffs or mountains where multiple impacts may be involved.

5.3.4.5.2. Methods of Study (227, 228, 230)

Data on human resistance to impact come from a number of techniques.

Volunteer subjects, often young adults, are used in controlled experiments. The limits are set by subjective criteria. Unfortunately the value of such research seems very limited. In practice the data obtained cannot be safely applied to all cross sections of the population (children, women and the elderly, for example). For many authors, the results obtained constitute the most reliable source of the physiological effects of impacts involving forces of low intensity.

When the limits to be explored become dangerous for man, recourse is made to anthropomorphic dummies, to human cadavers, and to anaethetised animals (monkeys). Some data very pertinent to the estimation of human resistance have been obtained, but the value of these results must be seriously questioned. No dummy or cadaver provides physiological data. The extrapolation to man of values obtained in animal experiments must always be interpreted with extreme caution.

Very thorough investigations of automobile or aircraft accidents have provided good information, although the forces involved and the environmental conditions are often difficult to determine precisely.

Despite malfunctions of their equipment, sport or military parachutists survive severe impact forces. Some pilots or crew members have jumped from aircraft in flight, without a parachute, and have survived. Falls, generally attempted suicides, have been systematically studied, in particular at San Francisco (Golden Gate Bridge) and in Australia (Sydney Harbour Bridge).

The different factors which determine the lesions have been especially studied by Snyder (227, 228, 230), first at the Office of Aviation Medicine at Oklahoma City (Federal Aviation Agency) and then at the Institute of Science and Technology at Michigan.

5.3.4.5.3. Physical Factors

Physical factors are the most important. The complexities of analysing free falls arises from the large number of environmental factors which can sometimes influence to various degrees the nature, size, and severity of the lesions. Some are calculated and some measured.

1. Amplitude

It has not proved possible to demonstrate a direct relationship between the height of the fall and the degree and severity of the resulting injuries. Snyder (230) notes that 90 individuals survived after free falls from between 30 and 274 metres, and 9 survived after a fall of more than 300 metres.

In some impacts, the magnitude of the forces reaches 35-300 G, according to the circumstances of the free fall. If the degree of deformation of the impact surface is measurable, it is possible to determine the value of the G factor with satisfactory accuracy. On the other hand, in cases of landing on concrete, steel or granite surfaces, the calculated forces are 70-100 times greater than those observed in experiments with volunteers.

The distance between the points of departure and of arrival having been calculated, it can be shown that the speed of the subject in free fall plays a part. At sea level a fall from 146 metres is sufficient to reach the terminal velocity of 162 km/h, but it must be noted that air resistance modifies the speed of fall of the human body.

2. Direction of Forces

The orientation of the body changes the nature, degree and severity of the injuries.

Head-first falls (-Gz) are the least well tolerated (except into water). With feet-first impacts (+Gz), the most severe injuries are to the feet, the ankles and the legs, but very serious fractures of the spine are not uncommon. With impact in the sitting position, the buttocks strike first, and vertebral and pelvic lesions predominate. With transverse impacts (+Gx) injuries to the upper limbs, thorax, spine and pelvis are most frequently encountered.

3. Distribution of Forces

De Haven (1942) showed that the larger the area of application of force, the lower the stress per unit area. This concept is generally valid, except for falls into water. In these, the smaller the area of contact, the greater are the chances of survival at a high impact velocity. For feet-first impact onto water (±Gz) where the area of contact is low (430 cm^2 on average for men and 290 cm^2 for women (230)) the orientation of the body reduces lesions to a minimum.

The absorption of energy by the lower limbs depends upon the posture of the knees. An impact with the knees straight allows the transmission of forces 4-6 times greater than the same impact with the knees bent. Some important factors are age, relative flexibility of the limbs, and experience acquired during paratroop training.

4. Area of Application

The extent of deformation of the material struck plays a role in determining injury. Snow has a compressive strength which varies as a function of several factors such as temperature, crystal structure and density.

The depth of penetration into water and the duration of the acceleration are both higher when the contact area of impact of the human body is smaller. The chances of survival are correspondingly greater.

5. Duration

The duration of application of the impact forces is the most important factor in determining human tolerance for impact. In free fall, this time is generally short (a few hundredths to a few thousandths of a second).

Stapp (293) has shown that if the duration of impact is less than 0.2 second tissues will suffer structural damage. They behave like an inert material under conditions of mechanical shock (233).

During certain impacts (jump from the window of a 6 storey building) mean velocities of 20 metres per second have been established, with a duration of deceleration of 0.004 seconds. The deformation of the surface of impact (concrete) caused by the force applied during this period of time was sufficiently effective to permit deceleration of the body with only minimal lesions (translator's note - Synder (230) cites this as an exceptional case not as the relatively common occurrence suggested by the authors).

At present, most authors agree with Snyder (230) that the various data obtained from studies of high impact velocity are inadequate for the precise understanding of the nature of the influence of the time factor on impacts after free fall. The values obtained in some accidents with minor injury considerably exceed those derived from experimental studies as the basis of survival.

5.3.4.5.4. Biological Factors

There is a close relationship between physical condition and impact tolerance. The highest speeds known have been seen in men and women trained to fall; tumblers, wrestlers, judo experts, acrobats, parachutists. Muscular relaxation appears to be the most significant factor.

5.3.4.5.5. Impacts into Water

The limits of human tolerance for water impact have directly applicable value, both for the escape of aircrew from combat aircraft and for the manoeuvres of parachutists.

Snyder (228, 230) studied 54 cases of unrestrained free fall from heights of 15 metres or more, giving an impact velocity of between 60 and 193 km/h.

The distribution of injuries varies with the direction of the forces. If the body is in a feet-first orientation, 32.3% of cases do not suffer clinically detectable injuries. Feet-first impacts produce:

- contusions of the thighs and buttocks
- compression fractures of the spine (D12, L1)
- pulmonary haemorrhages.

Feet-first (+Gz) or head-first (-Gz) impacts allow longer times for penetration and deceleration (Table 5.16).

TABLE 5.16

Theoretical Values of G-forces in Impact into Water, in Various Orientations (from Earley and Snyder (230))

Impact Velocity km/h	Head First (-Gz) Feet First (+Gz)	Lateral Impact (+Gx; ±Gy)
25	3.5 G	18.6 G
33	6 G	40 G
62	16 G	112 G
87	43 G	300 G

The professional divers of Acapulco leap from cliffs 30-40 metres high. The most experienced of them has performed 26,000 high dives in 25 years. Contact is made with the water at speeds of the order of 92 km/h, with decelerations of 40-45 G during the immersion of the head and shoulders. Schneider et al (204) found radiographic evidence of the existence of old fractures of the thoracic vertebrae in 4 of 6 divers examined. The fractures were at the level of D5 (1 case), D5/D6 (2 cases), and D2, D3, D4, or D7 (1 case each). These Mexicans dive with their arms stretched out in front, and the neck in slight hyperextension to hit the water with the top of the head. A second technique is to dive with the hands spread. If, by chance, the hands hit the head at the moment of impact, fractures of the ulna, of the radius, or of the metacarpals may be produced.

These studies show that survival with only minimal lesions is possible on water impact in the head-first position at speeds reaching 90 km/h.

Schneider and Snow (229) studied 169 cases of suicide from the Golden Gate Bridge at San Francisco. The distance from the parapet of this bridge to the water varies, depending upon the tides, from 72.9 to 79.6 metres. The speeds reached were from 82-120 km/h. Anatomical examination of 52 women and 117 men showed that the commonest mechanism of fatal trauma is crushing of the thoracic cage, with multiple bilateral fractures of the ribs, the fragments of which penetrate the lung, the liver and the spleen.

Fractures of the ribs occur in 85.2% of fatal impacts. In 76% of cases, the lungs are lacerated by the penetration of rib fragments. The liver is ruptured in 53.8% of cases. Cardiovascular trauma ranges from a simple contusion to the rupture of a major vessel or of a cavity of the heart. Each of 87 cases of cardiovascular lesions (with the exception of 5) was associated with multiple fractures of the ribs with penetration of the pleural or pericardial cavities. In 42 cases one or more cavities of the heart were ruptured, the left atrium being the most vulnerable. In 45 cases there was traumatic rupture or laceration of one or more great vessels, aortic rupture being the most frequent. Forty cases of fracture of the skull were noted as well as 62 cases of cerebral damage (subarachnoid haemorrhage). The kidneys were less often injured; 8 cases of contusion, laceration, or rupture were seen. Seventeen individuals had no fractures. In 45 cases the probable cause of death was drowning.

These injuries are characteristic of a fall in which the front, sides, or back of the body strike the water transversely (the resulting forces reach 300 G, for an impact velocity of 87 km/h).

The position of the body at the moment of impact seems to be a fundamental factor. Four people out of 411 who jumped from the Golden Gate Bridge in San Francisco hit the water feet-first and suffered no injury. In lateral and transverse water impacts, the main cause of death is the penetration of the vital organs of the thorax by rib fragments (R.G. Snyder).

5.3.4.5.6. Impacts at Terminal Velocity (227, 228, 230)

The human body in free fall reaches a constant velocity when the braking force of air resistance equals that of gravity. This speed is of the order of 162 km/h for a free fall of 147 metres at sea level.

The majority of survivals after impact at terminal velocity occur after falls into water or snow. Less commonly, a combination of water and mud assists the deceleration.

In Indochina in October 1950, during an operational drop from low altitude (150-300 metres) a failure occurred in the automatic opening of the main parachute and also of the emergency chest parachute. This French parachutist landed feet-first in a rice field. He was buried to a depth of about 30 cm above his head. Other members of the commando team landed close by and observed his floating helmet. They seized his arms, which were waving about, and pulled the parachutist from the mud. He had no apparent injury. In hospital after evacuation, fractures of the tuberosities of the right and left calcanea were diagnosed.

Kiel (149) reports another case observed during airborne manoeuvres in Alaska in February 1955. During the drop of a battalion of men from a height of about 430 metres on a clear, relatively warm day, an observer noticed what appeared to be a package falling from one of the C119 aircraft. No parachute opened above this object. The impact gave the impression of a mortar shell exploding in the snow. When rescue teams reached the site of the accident, they found a young black parachutist stretched out on his back at the bottom of a crater 1.06 metres deep in the snow. He could talk, and did not appear to have suffered injury. Examination in hospital revealed an incomplete fracture of the right clavicle, a fracture of L2 (anterior wedge compression) and various contusions of the skin. The average deceleration was calculated to be 141 G.

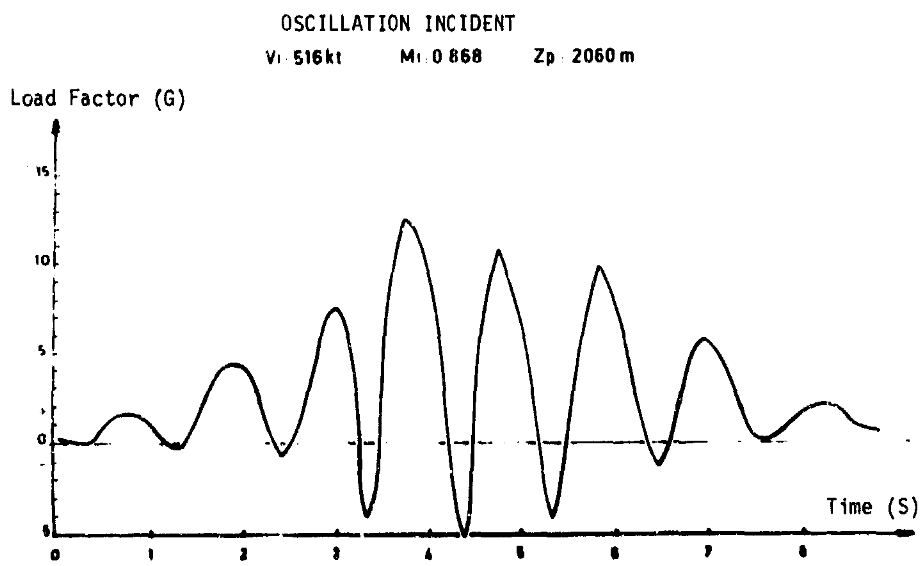
One of the most widely studied cases of this type of impact at terminal velocity was that of a RAF tail gunner, Sergeant Nicholas Alkemade, who jumped from a Lancaster bomber which was on fire (230). This aircraft was brought down by a night fighter of the Luftwaffe on 23 March 1944, at midnight. Because his parachute was in the front of the aircraft and could not be reached on account of the fire, this Scotsman jumped without it from a height of 5,500 metres. After 90 seconds of free fall at terminal velocity, he struck the snow-covered branches of some pine trees, before landing in less than 45 cm of snow only 20 metres from bare and rough ground. The only injuries to Alkemade found by German doctors were burns suffered before the jump, and superficial scratches.

Another recently published case is that of Adjutant Jules Coqueron, a radio operator/navigator of the French "Tunisie" Group of Bomber Command of the RAF. On the night of 22/23 January 1945 in a four engined Halifax 3B returning from a mission over the Ruhr (Gelsenkirchen), the pilot of the aircraft, which had only two functioning engines, decided to return to base at Elvington (UK) rather than landing at an emergency airfield. At a height of 2,400 metres fire broke out in one of the two remaining engines and damaged the undercarriage doors. The fire increased in intensity and began to invade the cabin. The order to evacuate the aircraft was given, and at the same time a large explosion occurred, followed by disintegration of the left wing. At 0 hours 47 minutes, Adjutant Coqueron fought his way to the navigator's escape hatch, the only possible exit. The navigator was stuck in the hatch, but by pushing and shoving, Coqueron succeeded in freeing him and went through the hatch. His first reflex was to try to open his parachute, but despite all his efforts, he could not release it. Rescuers found

him with his parachute still folded in its pack. In clearing the hatch, Coqueron had fractured his fifth cervical vertebra, and his motor function was seriously diminished. He fell in a pile of snow at the end of a cement path in a farmyard in the south of England. He whistled to summon help, and was rapidly transported to an American hospital specialising in the treatment of major spinal injuries.

The impact of Lieutenant Colonel I.M. Chissov of the Soviet Air Force is also interesting (230). In January 1942, he was Lieutenant-Navigator of an Ilyushin 4 that was attacked by a flight of 12 Messerschmitt aircraft of the Luftwaffe. He abandoned the burning aircraft but, because of the presence of the enemy aircraft, he was reluctant to deploy his parachute, and intended to do so at a lower altitude. However, Chissov suffered loss of consciousness and did not open his parachute. He had the good fortune to land on the edge of a ravine, the slopes of which were covered with about a metre of snow. Rescued by the Russian cavalry, he was taken to hospital with a fracture of the pelvis and "spinal concussion".

Impacts at terminal velocity sometimes occur in some ejection situations (at low altitude) (230). It is possible that in the dynamic phase, before the opening of the personal parachute, ejections in mountainous regions might result in the impact of the pilot with snow-covered slopes. Several cases have been reported by Snyder in the USA.



Variation in Load Factor

Figure 98. Oscillation incident - Variation in load factor.

Vi = 516 Knots Zp : 2060 m (CEV Brétigny-sur-Orge)

5.3.5. Fractures of the Spine in Flight

R.P. Delahaye and R. Auffret

SUMMARY

Introduction

Fractures of the spine can occur in the pilot of a combat aircraft during one of the phases of flight. They appear:

- during rapid vibrational phenomena (induced oscillations)

- with inadvertent unlocking of the seat, an event producing additional accelerations which lead to sudden compression of the vertebral column.

During turbulence, a flight attendant thrown against the wall or the seats of an aircraft sometimes presents with a fracture of the spine. More rarely, cervical sprains have been described during aerobatics (36).

5.3.5.1. Induced Oscillation ("Pumping")

1. Definition and Description (3, 8, 74, 138, 198, 245)

Pilot-induced oscillation (for which the French term is "pumping") is a phenomenon which has been known in aircraft since the introduction of servocontrol systems. This phenomenon is not peculiar to aeronautics; it exists in all man-machine systems using servocontrols when corrections by the operator produce an effect opposite to that sought, leading, for example, to the amplification of the movements of a vehicle when the intention is to damp them out. Induced oscillation may cause loss of control of an automobile as well as an aircraft or helicopter.

In aeronautics, the first reports of induced oscillation passed relatively unnoticed, because the load factor produced by the oscillation was often relatively low; it caused neither an accident nor any effect upon the structure of the aircraft or the well being of the pilot.

However, in an aircraft with more complex and sophisticated controls, these oscillations are known, in high speed flight, to produce damage to the aircraft and injuries to the pilot. Moreover, the potential risks of induced oscillation during flight at low altitude and even as a cause of some accidents, compel aircraft designers to investigate the phenomenon and to modify the flight control laws to avoid inappropriate coupling between the man and the machine.

The origin of induced oscillation may lie in an involuntary command from the pilot during a poorly-judged action, as well as in demands external to the act of firing; atmospheric turbulence, functional anomalies of the servocontrols etc.

At high aircraft speeds, small movements of the controls provoke aircraft movements of large amplitude. The resulting accelerations, most often in the longitudinal axis of the aircraft, lead to a succession of +Gz loads followed by high values of -Gz acceleration. Fig. 99 shows the changing accelerations recorded in flight during such an episode (245). These oscillations are generally amplified by the corrections which the pilot attempts to apply by his manipulation of the controls, because of the possible phase shift of the corrections. This phase shift is associated with the lag between the actions of the pilots and the reactions of the aircraft.

In fact, for rapid phenomena of the order of 1 Hz, there is a delay in the man-aircraft link - between the sensation of the pilot, his reaction, and the action of the controls - because of delays in transmission between these various stages which involve not only the human reaction time but also the response time of the servocontrol circuits.

Pilot-induced oscillations can appear in all servocontrol systems under the command of the pilot; thus, they affect all three axes of the aircraft, and can also occur at low aircraft speeds in flight close to the ground (approach, landing, take-off), with an increased risk of accidents due to the proximity of obstacles.

In some cases of induced oscillation, the absence of a response from the pilot may moderate the development of the incident. Very delicate "finger tip" flying is certainly better than muscular action involving several segments of the limb. Moreover, when the oscillations are large, any co-ordinated voluntary action by the pilot is almost impossible. Everything happens very quickly; the magnitude and frequency of the accelerations lead to uncontrolled and uncontrollable movements of the arms, the legs, and the head. Fortunately, in most cases of uncontrollable oscillation at low level, the aircraft goes into a climb, either of its own accord, or because of the pilot's efforts to ensure his immediate safety.

These oscillations sometimes lead to permanent deformation of the structure and wings of the aircraft. The loss of external loads (tanks, engines, weapons) is common when the structural limit of anchorage points is reached.

2. Case Histories

Case I; Circumstances of the Accident (Extract from the Board of Inquiry)

"The pilot took off as No. 3 of a flight of 4 Mirage IIIE aircraft on an attack mission. The take-off was normal. In a straight climb, passing 1500 feet at a speed of 300 knots, the pilot levelled off and cut the afterburner. Level flight lasted for about 5 seconds. The pilot noted a speed of 300 knots, and a height between 1500 and 2000 feet.

The leader called for a turn to the left. Trying to rejoin his leader, the pilot began a slight turn, banking the aircraft 10° to the left and pulling back on the control column. With the first demand on the controls, the aircraft departed very abruptly, and dived at an angle of 20-30° with the wings virtually level. It was a fierce negative G stall, and not a transient oscillation.

The pilot pulled back on the stick and engaged the afterburner. He had the feeling that the aircraft did not respond, although the control column was fully back. He then grasped the column with both hands and pulled very hard. The aircraft started to buck violently. The pilot was then severely shaken, subjected, as he said 'to violent lurching in all directions' as if he felt the effects of shaking in a very tight spin. He remembers having seen his flight log pass before his eyes at least 3 times. He could not read the instrument panel. After a time which the pilot is unable to judge even approximately, control of the aircraft was regained in a climb at an angle of 30° at an altitude of 6,500 feet. The accelerometer showed that the maximum limits of +G and -G had been reached; the tell-tale needles were stuck at +9.5 G and -5 G. The pilot then reported the loss of his auxiliary tanks (Fig. 98).

The pilot had difficulty in expressing himself on the radio. He switched to the IFF emergency frequency, and at that moment he began to feel violent backache. He came in to land without other incident, after some low speed passes. The landing was normal. The engine was cut on the runway" (extracts from the report of the inquiry).

Still suffering from back pain, the pilot carefully left the cockpit, helped by another pilot who was at the end of the runway. The pilot's seat harness was particularly tight.

Cause of the Accident

The difficult but very thorough investigations carried out by the Commission of Inquiry determined that the initial cause of the accident was a sudden complex mechanical failure, simultaneously affecting two components of the autocontrol system. When the pilot operated the control to begin his turn to the left, this double failure caused a sudden cut-out of the power controls leading to forward movement of the control column and the abrupt dive of the aircraft at an angle of 20-30°.

Results of the Accident; the Accelerations Sustained

The consequences of this sudden mechanical failure were the application of successive stages of acceleration which led to fracture of the spine. From the sudden "departure" of the aircraft in the dive when the malfunction occurred until the recovery of a normally-controlled aircraft at an altitude of about 6,500 feet, a series of very violent positive and negative accelerations occurred in the pitch axis. More complex accelerations were probably also experienced in this phase. Indeed, the pilot said that he had the impression of being in an upward spin.

Pathological Effects Produced by the Accelerations

From the end of the incident after stabilisation of the aircraft at about 6,500 feet, the pilot experienced back pains. Although they were mild enough during the terminal phase of flight to allow the pilot to carry out a normal landing, these pains increased in intensity during the half hour after leaving the aircraft.

Clinical examination was carried out immediately, and the symptoms were aggravated by percussion of the spinous processes, in particular. It was not possible to elicit a localised pain. There was also a generalised spasm of the paravertebral muscle masses. Neurological examination was normal.

Standard radiograms of the thoracic spine revealed the existence of two compression fractures of D4 and D8, with moderate wedge-shaped deformation. The posterior wall was intact. The radiological appearance of the cervical and lumbar regions was normal. Unfortunately, it was not possible to compare this radiological picture with reference plates. In fact, at the time when this fighter pilot was recruited (August 1957), systematic radiographs of the spine were not mandatory.

Lateral tomograms obtained 4 weeks after the accident confirmed the existence of post-traumatic lesions: fracture of the anterior superior corner of D4, fracture of the lower anterior corner of D8. The structure and morphology of the posterior wall were normal.

Subsequent Data

The painful thoracic symptoms regressed after several days of absolute bed rest and treatment with analgesics and relaxants. After the disappearance of the acute pain, gentle spinal exercises were given progressively. Thirteen weeks following the accident the pilot was declared fit for graded return to flight, after radiological monitoring at CEMPN in Strasbourg had shown excellent consolidation. The return to flying, under medical supervision, was accomplished without notable incident.

Case II (from the Board of Inquiry)

"On 25 June 1972, the pilot of Mirage IIIC, during a low altitude flight over the base (on an Open Day), was in position No. 2 of the formation, climbing with left bank. Without any movement of the control column, the aircraft went into very violent oscillations. In 1.5 seconds, three very severe oscillations were experienced. The accelerometer was against the stops (-5 G, +10 G). The pilot states that he had the impression that his head struck his knee three times. The restraint harness was correctly adjusted. To the medical examiner, the pilot reported that he had cervical, thoracic and lumbar pain. In particular, he had a severe pain in the lower lumbar region. The condition developed progressively into a picture of hyperalgesic sciatica caused by herniation of the disc at L5, surgical excision of which produced a good result.

3. Pathogenesis (Fig. 99)

Two types of lesions may be observed:

- fractures

- herniated discs.

The site of these lesions depends on the value of the force required to rupture the nucleus pulposus. Experimentally, the limit for mechanical displacement of the disc during vertebral trauma lies at about D9/D10. This is why, in the dozen severe cases of induced oscillation observed in the Air Force and in test personnel (Bretigny sur Orge), fractures of the thoracic spine and pathology associated with displacement of the nucleus pulposus (prolapsed disc) were found.

The forces applied generate accelerations of large amplitude and short duration, much larger than those indicated by the limits of the accelerometer, which are often exceeded (-4 Gz to + 9.5 Gz). The aetiology of fractures in the upper thoracic spine (D4 to D7) is an abrupt change from a negative load factor to a positive one. But an additional factor comes into play, which does not exist during an ejection; the extremely rapid recurrence of negative and positive accelerations engendered by the oscillations of the aircraft in the pitch axis.

The rapid oscillations (1 per second) profoundly modify the vertebral equilibrium:

- during the rapid rise of +Gz acceleration, the pilot is forced into his seat, with his spine in hyperflexion despite the tight restraint

- half a second later, acceleration occurs in the opposite direction; the pilot is then abruptly thrown upwards and leaves the seat before he has time to push himself down into it.

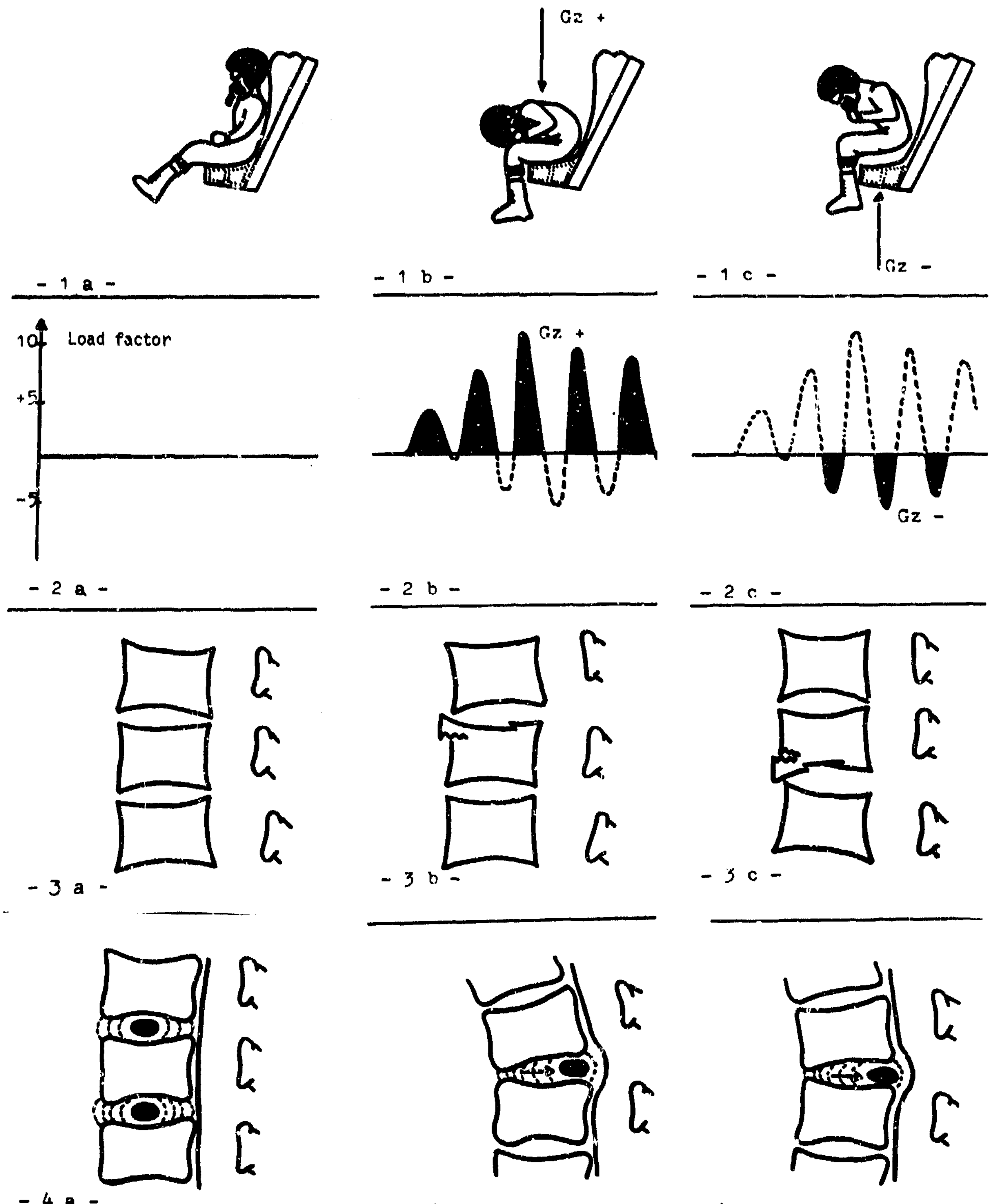


Figure 99. Oscillation incident.

1) Effect of accelerations on pilot posture:
   a) normal posture b) +Gz c) -Gz

2) Variation of load factor:
   a) normal b) +Gz c) -Gz

3) Effect on thoracic spine
   a) normal appearance b) fracture of upper vertebral plateau
   c) fracture of lower vertebral plateau

4) Effect on lumbar spine
   a) normal appearance b) displacement of nucleus pulposus with tendency to herniated disc
   c) herniation scarcely affected by Gz accelerations

Compression fractures occur by mechanism I or II of Watson-Jones. It is certain that an asymmetrical sitting position (with one thigh less supported than the other) aggravates the problem caused by the transmitted accelerations. These fractures can involve:

- an upper or lower vertebral end-plate, in isolation;

- both-end plates, generally of two different vertebrae; the superior surface of D4 and the inferior of D6, for example.

At the level of the lumbar spine, hyperflexion pushes the nucleus pulposus backwards rapidly, and there is no time for a change in the direction of its movement during the reversal of acceleration. This is why herniation of the disc with all its possible clinical variations, can occur as an immediate consequence of severe induced oscillation.

5.3.5.2. Unlocking of the Seat

Inadvertent unlocking of the seat during a tight turn can lead to spinal fracture (4 cases are known in the Air Force and in flight test personnel).

Case History (from Board of Inquiry) (180)

On 2 September 1970, returning from an interceptor mission, the leader of a patrol was in the No. 1 position at the break for landing at 1500 feet. During a relatively tight turn (about 4 G) when the pilot was leaning slightly forward (lowering the landing gear) the seat unlocked and dropped abruptly to the bottom of the cockpit (through a distance of about 15 cm). The pilot then experienced an extremely severe pain at thoracic level, which caused intense dyspnoea.

Despite poor visibility, he succeeded in landing the aircraft normally, parked it, left the cockpit unaided, and sought medical help. A clinical examination was made immediately and revealed a painful area centring on D7/D8. Radiography and tomography of the spine showed a fracture of D7, with damage to the upper plateau.

In this case the pathogenic mechanism was associated with:

- an initial moderate acceleration (+4 Gz) of long duration

- a superimposed intense +Gz acceleration of short duration, caused by the abrupt descent of the seat to the bottom of the cockpit. It may well have reached several tens of G.

Although the secondary acceleration due to the fall of the seat could not be precisely estimated, it must be accepted that the conditions in this case were quite similar to those of an impact, the consequences being further aggravated by the poor position of the pilot. Upon the impact of the seat with the floor of the cockpit, slight flexion of the spine occurred, which explains the occurrence of wedge compression.

The sites of the fractures in the four cases were D7 (3 times) and D8 (once). They were always of little significance, and they were confined to the upper vertebral surface.

5.3.5.3. Turbulence

By throwing flight personnel off balance, violent turbulence can project them against the walls of the aircraft, or a seat. Fractures of the thoracic or lumbar spine may occur (body or transverse processes). This was the case in a hostess aboard a McDonnell Douglas aircraft on 8 August 1975.

5.3.6. Accidents in Centrifuges and Experiments (Ejection Seat Training Towers, Sleds)

R.P. Delahaye and R. Auffret

SUMMARY

Traumatic injuries of the spine, and particularly fractures, have been described during experiments on centrifuges, on rocket sleds, or on ejection seat training rigs.

5.3.6.1. Centrifuges and the Spinal Column

Spinal injuries caused by a ride on the centrifuge have been very rarely reported in the medical literature. However, we have several times been asked to give circumstantial opinion on the vertebral pains developed by some experimental subjects after centrifuge runs.

We have been able to trace in particular the rapid development of a cervical arthritis with especially characteristic clinical and radiological signs. This disorder appeared immediately after a test carried out on the centrifuge of the Aerospace Medical Laboratory of the Flight Test Centre (CEV) at Bretigny sur Orge.

5.3.6.1.1. Performance Characteristics of the Centrifuge at CEV, Bretigny (Figs. 100 & 101)

This centrifuge, which was built in 1955, has been operational since 1956. It consists of an arm 6 metres in length rotating about a vertical axis. At the end of the arm is a gondola in which human subjects, animals, and items of equipment can be exposed to accelerations produced by centrifugal force. Electrical and recording circuits, which are not part of the main drive, run to a circular room located above the arm. Photographic or tape recorders of the type used in in-flight tests reproduce the recordings. In addition, television and cine photography are used to monitor the test subjects.

Different interchangeable free-swinging gondolas are used, depending on the type of experiment:

- a large gondola, 3 metres in diameter, in which the seat mounting can be oriented in four directions at 90° to each other;

- a cabin of an Etendard II aircraft, completely equipped with controls and instruments, which can be programmed by an analogue computer (different phases of flight can thus be simulated under acceleration);

- a high performance gondola, most often used for tests of equipment

- special fixed gondolas for tests on bulky equipment.

5.3.6.1.2. Test Protocol (6)

By virtue of catapult launching of the centrifuge, it is possible to attain an acceleration profile close to that of an ejection. With the large gondola, 13.5 G can be reached in 1 second; a time longer than in an actual ejection, but the 0.8 second duration of the plateau at 13.5 G, followed by braking in 1 second, gives results similar to an ejection.

Figure 100. Centrifuge at the Aerospace Medical Laboratory - Centre d'Essais en Vol de Bretigny-sur-Orge.

Figure 101. Pilot sitting in Martin Baker AM4 seat installed in the cabin of the centrifuge at CEV, Bretigny.

For the high centripetal acceleration produced by the centrifuge to be directed in the long axis of the body, the subject must be placed virtually horizontal, with the head towards the axis of rotation. The very short launch time does not allow the use of a "free" gondola, which swings under its own inertia. Instead, it is necessary, before the launch, to align the gondola manually so as to bring the major axis of the body into line with the axis of the arm carrying the centrifuge gondola. This uncomfortable position makes it difficult for the subject to place his back correctly on the Martin Baker Mk 4 seat used. Monitoring of the subject is carried out by television. Two 16 mm black and white cameras record frontal and lateral displacements of the head.

Acceleration in the Z axis, the electrocardiogram, and rheography of the base of the skull are recorded in each test carried out at progressive levels of acceleration: 6.5, 9, 11.5, and 13.5 G.

5.3.6.1.3. Results

Studies at 6.5 and 9 G

No subjective symptoms, loss of consciousness, or impairment of vision were reported by the subjects. However, the occurrence of back pain at the level of D7/D8/D9 must be noted, especially after repeated tests.

Studies at 11.5 G

The acceleration began to exert a significant stress upon the test subjects. Neither loss of consciousness nor blurring of vision was reported. However, acute back pains were invariable, but they lasted only a few hours.

Studies at 13.5 G

Only one test was carried out, on a test pilot aged 35 years. He had no visual symptoms or loss of consciousness. A very significant compression of the subject was visible on the cine films. It was of the order of 15 cm.

Subject R.A. was in a lying position at the onset, with his back poorly positioned against the seat back. Moreover, during this test at 13.5 G a slight side-slipping of the gondola occurred, which generated complex angular accelerations at the level of the cervical spine. In the days following the test, R.A. suffered pain at the level of C6/C7, at first stabbing and variable and later with exacerbation at night and sensory disturbance in the C6/C7 distribution. The pain was very severe, and aggravated by any active or passive movement. Neurological examination showed the existence of a Babinski response on one side indicative of nerve trauma, and revealed the presence of a root lesion affecting the left upper limb with loss of the triceps and ulnar reflexes on that side.

A radiological picture typical of arthritis of C5/C6 and C6/C7 rapidly developed, with overall narrowing of the C6/C7 interface, increased density of the end plates of C5/C6/C7, and marginal osteophytosis which was particularly clear at the level of C6/C7. Recent radiological records (made less than 3 months earlier) of this pilot R.A. made it possible to follow the very rapid development of this post-traumatic arthritis. The intervertebral foramina of C6 and C7, which were small, also showed classical morphological changes of the type commonly described in vertebral arthritis.

After immobilisation in a Minerva plaster for three months followed by the intermittent wearing of a plexiglass splint for two months, functional recovery was complete. No neurological deficit remained.

Syndromes of vertebral pain with radiological change probably result from the combination of accelerations in the Z (longitudinal) and X (transverse) axes when the centrifuge starts and stops. They are analogous to those which occur when the seat fires in complicated ejections with a poor body posture. These painful symptoms develop more rapidly when the intervertebral foramina are small and when the intervertebral discs have suffered previous damage.

5.3.6.2. Accidents on Ejection Seat Training Rigs

Accidents are rarely seen on ejection seat training rigs. They are most often attributable to malfunction of the seat or to modifications to it.

The acceleration recorded on such rigs is much smaller than that of a real ejection. Cooper and Holmstrom (USAF) (42) reported the results of 200 tests carried out in 1950 on a rig producing 9 G with an onset rate of 100 G per second. These authors observed 4 fractures of the coccyx. They found that, because of the use of a very soft seat cushion, there was considerable amplification both of the amplitude (13.5 G) and of the rate of onset (500 G per second in one case). In other cases, the part played by the sitting position of the pilot on the ejection seat or the functioning of the seat firing system were implicated.

This form of training was abandoned in the French Air Force more than 20 years ago. No vertebral fractures had been observed in personnel using these test rigs.

5.3.6.3. Accidents on Rocket Sleds

These are very rare, because experimental protocols demand careful checking of the restraint of the experimental subject. As long as the harness is correctly adjusted and the braking of the rocket sled does not produce acceleration amplitudes in the +Gz axis which are too high, no fractures of the spine are seen, but if these conditions are not observed, the hyperflexion produced by the +Gz acceleration gives rise to fractures in the thoraco-lumbar column. We have examined the clinical and radiological records of several people injured during such tests, which have been sent to us from foreign aviation medicine centres for study and for opinion in connection with compensation.

5.4. CLINICAL EXAMINATION OF SPINAL INJURIES

P. Doury and G. Leguay

SUMMARY

5.4.1. Clinical Examination of the Spine

Clinical examination of the spine always follows history-taking and precedes radiological examination.

The examination includes manipulation of the subject in the erect, sitting, or lying position. In cases of severe injury this clinical examination must, of course, always be cautious, usually with the patient lying on his back.

5.4.1.1. Examination of the Upright Subject from the Front

This checks the equilibrium of the pelvis, that a line between the anteriosuperior iliac spine and the iliac crests is horizontal, that the shoulders are level, and that the thorax is symmetrical.

5.4.1.2. Examination of the Upright Subject from the Back

The subject being examined stands with his feet together. The examiner sits behind him and holds the knees of the patient between his own. He checks:

- the balance of the pelvis
- that the line joining the posteriosuperior iliac spines is horizontal
- the symmetry of the gluteal folds, which should be at the same level; the intergluteal cleft should be vertical
- that the spine is vertical and straight.

Forward flexion of the spine, with the legs kept straight, allows the distance of the hands from the floor, and thus the flexibility of the lumbar spine, to be assessed. For this test, it is necessary to check the functional integrity of the hip joints which obviously take part in this movement.

Anterior flexion also allows the absence of gibbosity to be confirmed by rotation of the vertebral bodies. The examiner, located behind the subject, examines the spine and the paravertebral musculature in an oblique light. During flexion, the muscle masses should stand out in a horizontal line. Schober's index is calculated by measuring, during forward flexion, the increase in the distance between two horizontal lines:

- one at the level of L5/S1
- the other 10 cm above the first when the subject is upright.

Normally, the increase is 5 cm.

Lateral flexion to the right and the left should show smooth curvature of the spine without rigid segments or angulation. The movements should not be painful. Extension or backward flexion of the spine should also be painless.

All these movements are carried out by the patient, while the examiner follows the movement executed by the subject.

5.4.1.3. Examination of the Upright Subject from the Side

This shows the absence of thoracic hyperkyphosis, lumbar hyperlordosis, and hypotonia of the abdominal musculature. The distance between the occiput and the wall against which the subject stands is measured, and should be zero.

5.4.1.4. Walking on the Heels and Toes

Walking on the heels examines the motor function of the dorsiflexors of the foot, which are innervated from L5, and walking on tiptoe tests the motor capacity of the gastrocnemius and soleus, which are innervated from the S1 root. This completes the examination of the upright subject.

5.4.1.5. Examination of the Seated Subject

This assesses the axial rotation of the trunk. The subject sits facing the examiner who grips the knees tightly between his own to immobilise the pelvis. He holds the subject by the shoulders and makes him carry out a rotary movement of the trunk. This movement, which should be painless, involves the thoraco-lumbar junction.

5.4.1.6. Examination of the Supine Subject

This confirms the equality of the following distances on the two sides; from the anteriosuperior iliac spine to the internal malleolus, from the umbilicus to the internal malleolus, and from the greater trochanter to the external malleolus.

Lasegue's manoeuvre consists of flexing the hip with the leg extended. Normally this movement causes no pain in the lumbar region or in the lower limbs. Attempts to separate or to appose the iliac crests should not cause sacro-iliac pain.

5.4.1.7. Examination of the Prone Subject

This comprises palpation of the vertebral spines, and searching for a dimple over a spinous process, which indicates the existence of spondylolisthesis. Palpation of the paravertebral gutters by running a finger along the line of the spinous processes should be painless.

The examination of the normal spine should obviously be completed by neurological and gynaecological examinations, and examination of the abdomen and the lumbar fossae.

5.4.2. Clinical Examination of Spinal Trauma

A fundamental point must be made at the outset; whatever the site of the fracture, there are fractures of the spinal column with clinical manifestations and fractures that are asymptomatic. This distinction, which is nowadays generally recognised, justifies systematic radiography after any trauma that results from flight.

5.4.2.1. Fractures with Clinical Signs

1. Thoraco-lumbar Fractures

Pain is the essential manifestation of simple fractures of the spine. It has several characteristics:

- after the transitory state of shock, the intensity of which is more related to the violence of the trauma than to the lesion, a sometimes violent pain appears immediately after the lesion; it then leads to considerable functional disturbance

- in some cases the pains are moderate at first, but increase in intensity some hours after the trauma

- sometimes the pain is so transitory that it passes unnoticed and the casualty continues with his activities: several pilots, after ejection at night, have had to walk several kilometres to find a police station, despite the presence of fractures of the thoraco-lumbar spine.

A poor examination will often disclose few positive signs. Inspection sometimes shows the presence of ecchymoses or of wounds caused by direct impacts. Palpation and percussion reveal a localised pain over a lower thoracic or lumbar spinous process which may be accompanied by spasm of the sacrolumbar muscles. The pain, at least when it is of average intensity, is brought on by coughing and by physical effort. Sometimes an abnormal separation between two spinous processes or a step-like separation of one on the other may be seen.

Examination of the nervous system is very important. The casualty will complain of inability to move his legs and of loss of sensation in them. This paralysis is generally of immediate onset, but it may develop later, when he is moved, or on the radiodiagnostic table.

Examination shows a motor paralysis of the feet and legs. It is a flaccid paralysis with loss of the patellar reflex (353). Paralysis of the thigh muscles is sometimes difficult to confirm when there is an associated fracture of the shaft of the femur. All forms of sensation should be carefully tested and the upper level of their disappearance should be recorded.

More rarely a cauda equina syndrome is observed.

2. Cervical Fractures

Benassy (260) emphasises the range of a disconcerting variety of lesions. Attention may initially be attracted by;

- the presence of cervical pain, with an abnormal posture of the head and neck resembling torticollis

- difficulty with voluntary movements of the neck, which must be investigated with the greatest of caution. Account must be taken of associated facial injuries

- the presence of root symptoms: prickling or pins and needles in a localised area on one or both sides.

Clinical examination may show ecchymoses or wounds caused by direct impact. Excessive prominence of the cervical spines or an exaggeration of the suboccipital fossa may sometimes be evident.

The neurological examination should look for early signs of disturbance of objective sensation. For Benassy (260), their discovery has as much value as the patient's description of his pain. It is therefore necessary to define the topography of each of these pains:

- C1 has a limited distribution, without interest

- C2 (the greater occipital nerve of Arnold) has a territory running from the upper part of the neck to include the whole of the scalp

- C3 - the anterolateral area of the neck

- C4 - the base of the neck and the upper part of the thorax.

The following five roots have almost no representation on the trunk, and their sensory territory is confined to the upper limbs:

- C6 covers mainly the area of the thumb and the outer border of the index finger

- C7 - the next four adjacent sides of the fingers (median segment of the hand)

- C8 - the three remaining sides of fingers and the hypothenar eminence

- D1 covers the inside of the arm and the axillary region.

Monoplegia, hemiplegia, quadriplegia, and Brown-Sequard syndrome may be detected, but they are relatively uncommon in aviation trauma.

The absence of correlation between clinical and radiological findings must be remembered. A quadriplegia can appear without bony injury. Sometimes, a fracture dislocation is indicated only by a slight torticollis.

5.4.2.2. Asymptomatic Fractures

Simple fractures of the spine are clinically silent in 15-20% of cases. The most searching examination cannot, in such cases, provide sufficient evidence to eliminate with certainty a fracture of the spinal column.

5.5. RADIOLOGY OF SPINAL TRAUMA IN AVIATION MEDICINE

R.P. Delahaye and P.J. Metges

SUMMARY

Introduction

The importance of radiological examinations in the diagnosis of traumatic lesions of the spine in flying personnel and parachutists is now widely recognised and admitted. In many Air Forces, this investigation is mandatory and immediate after an accident or ejection. It should include the whole of the spine.

In the majority of cases, the fractures are thoraco-lumbar and, more rarely cervical. The immediate or early risk in unstable fractures is neurological (spinal cord or, primarily, nerve roots). Painful sequelae (see Chapter 5.6.) appear when post-traumatic deformation exceeds the limit of individual tolerance.

5.5.1. Radiological Techniques (262, 266, 283, 293)

Radiology detects sub-clinical injuries, and localises their site and the number and type of lesions. It provides guidance on the form of treatment.

Radiological examination of the spine in aerospace medicine does not differ from that of any recent spinal trauma, and it obeys the same principles:

- radiological examination should be carried out as soon as possible after an aviation accident

- the entire spine should be X-rayed segmentally, with frontal and lateral films (52, 270)

- multiple fractures of the vertebral column occur in 10-15% of cases, and we have the impression of a tendency for them to increase in recent years

- the plates should be as perfect as possible

- the post-traumatic diagnostic examination is carried out with the patient supine and immobile: the extent of the damage caused by trauma cannot be judged before examination of the radiographic plates; ill-judged mobilisation is liable to lead to neurological complications by displacement at an unstable focus

- depending upon the results of standard segmental radiograms, the radiologist may later be led to carry out complementary examinations using localised exposures, and frontal and lateral tomography, which permit a more detailed analysis of the lesions seen (286, 287, 288, 293, 294, 371).

The responsibility of the radiologist consists of:

- the technique of making the films

- the interpretation

- the conditions for return of the casualty to the emergency ward or to the orthopaedic department.

Given these principles, the radiological examination consists of diagnostic radiography and complementary radiological assessment (localised and oblique views, tomography, dynamic films, examinations with contrast media, scanning).

5.5.1.1. Diagnostic Radiograms

Diagnostic plates are made on large films (36 x 43 cm), in the frontal and lateral planes, segment by segment, to cover the entire vertebral column. The patient is not moved; he lies supine until the radiologist has examined all the plates made in this way, looking for lesions and assessing their basic stable or unstable character. It is necessary to make supplementary exposures of the cervico-occipital joint, upper thoracic, lumbosacral, and especially thoraco-lumbar regions. The latter visualise without distortion the vertebrae which are most often the site of traumatic lesions.

5.5.1.2. Supplementary Radiological Examinations

According to the circumstances, some special examinations are carried out immediately after diagnostic radiography; others later.

1. Localised Negatives and Oblique Views

These are centred on the region of the injury, and allow a more precise study of the vertebral and disc lesions. The oblique views are reserved for the study of the intervertebral foramina, articulations, isthmuses, and laminae. Tomograms from the same angles give radiological information on the condition of these anatomical structures.

2. Tomograms

Tomograms from the classical frontal and lateral aspects are systematically carried out in the radiology departments of the Bégin and Dominique Larrey Hospitals whenever a fracture of the spine is discovered. They yield pictures, of a quality that permits detailed analysis of the lesions observed (286, 287, 288, 293, 294, 371).

3. Dynamic Study

This may be undertaken if there are no radiological signs suggesting an unstable fracture. It examines the mobility of the spine, which is often greatly diminished by muscular spasm at the time of the trauma. It may be necessary to repeat the examination when the spasm has decreased.

Dynamic radiography plays an especially important role at the level of the cervical spine. In the diagnosis of sprains it confirms the integrity or injury of the interspinous ligament (widening of the space between the spinous processes) and of the disc (narrowing of the disc space; or localised widening). These plates are also of value in the study of the sequelae of fractures of the cervical and lumbar spine, and for assessing their functional effect on spinal geometry.

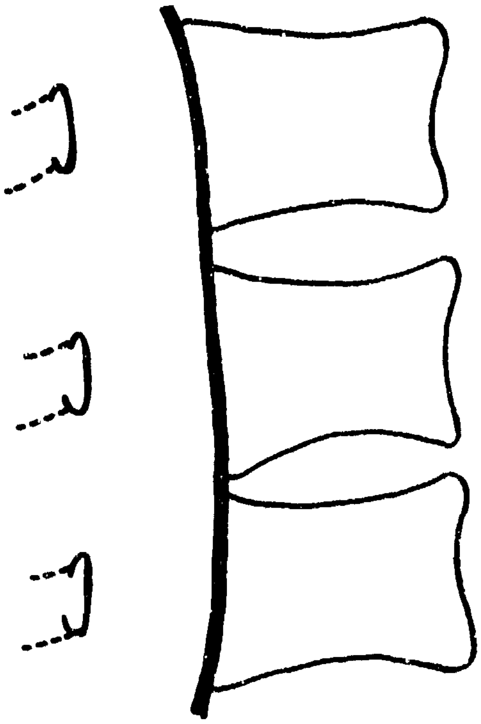


Figure 102. The integrity of the posterior wall can be confirmed by examination of the posterior elements, which form a continuous and regular line
(from Delahaye et al, 294).

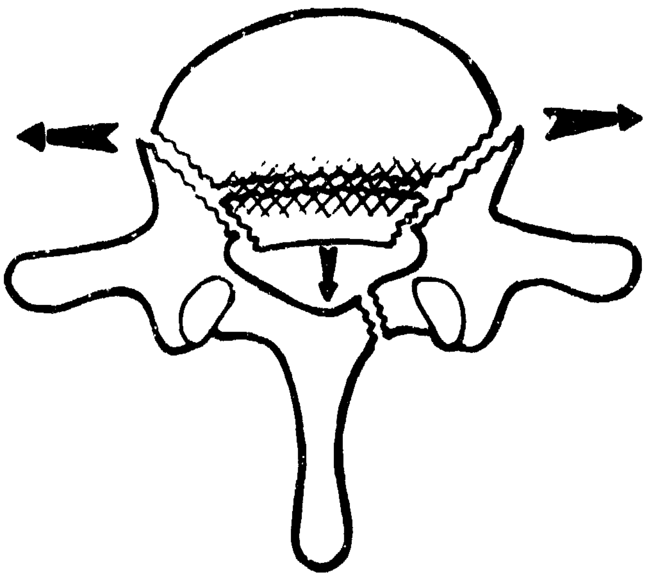


Figure 103. Fracture involving the "wall of resistance" and leading to separation of the pedicles (from Delahaye et al, 294).

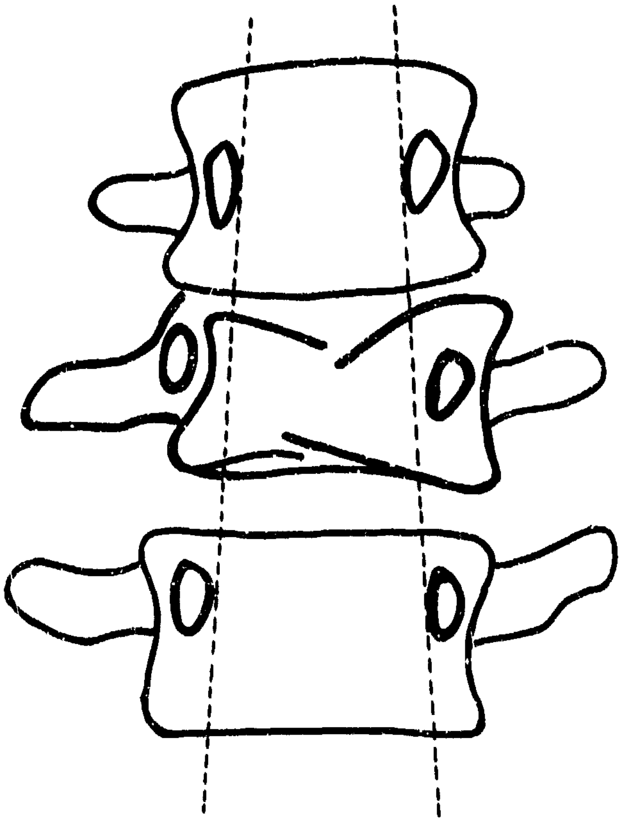


Figure 104. Assessment of the interpedicular distance; when it is increased, an unstable fracture must be suspected.
(from Delahaye et al, 294)

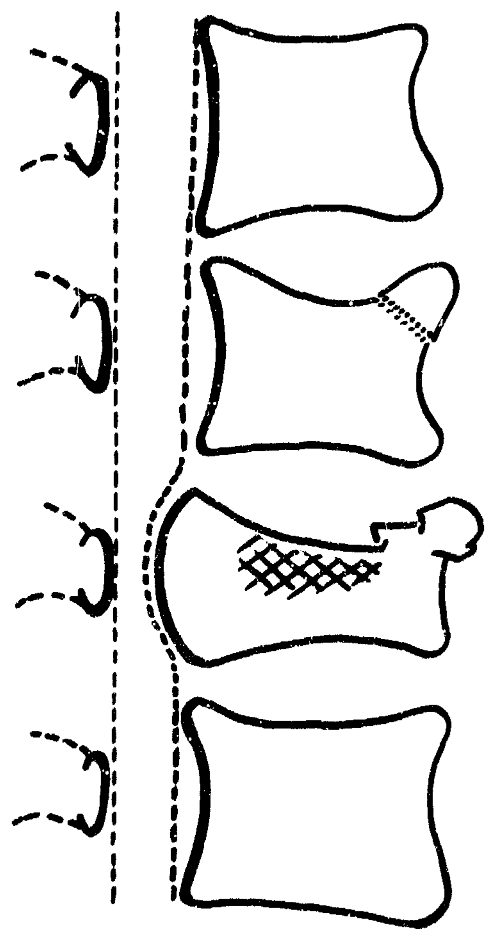


Figure 105. Injury to the wall of resistance (protrusion).
(from Delahaye et al, 294)

4. Examination by Gas and Opaque Contrast Media

Contrast radiography ("Amipaque" - metrizamide) is indicated in cases of secondary canal stenosis and of post-traumatic herniation of the disc (362). Spinal angiography has been used by Djindjian and his school (269) in cases with neurological lesions.

5. Scanning

This provides horizontal cross sections of the vertebrae which very well delineate the posterior arch and the spinal cord. This examination helps in the evaluation of complex lesions of the posterior arch, and reveals pre-fracture haematomas at injury sites, and immediate and late stenosis of the canal (347, 361).

5.5.2. Radiological Signs of Fractures of the Spine

Fractures and dislocations of the spine are dominated by the drama of a complete spinal cord lesion accompanying the fracture, and by the spectre of secondary neurological complications. These are the unstable traumatic lesions, several degrees of which can be responsible for the neural damage. The vertebral integrity or stability which gives the spine its strength and restricts its mobility is disrupted. In such conditions, any vertebral displacement, during movement or due to trauma, in excess of physiological limits, makes the vertebral deformation greater and injures the neural structures. The primary role of the radiologist is, by radioclinical studies, to diagnose vertebral instability and to make as complete an analysis as possible of bony and ligamentous lesions and of their effects on spinal geometry and the spinal canal.

We shall begin by discussing vertebral instability and later we shall detail the signs of all bony and ligamentous lesions.

5.5.2.1. Vertebral Instability (261, 279, 336, 337, 386, 448)

Instability at the site of a spinal fracture or dislocation implies a latent pathological mobility which can exceed physiological limits. Its origin may lie in bony lesions (temporary instability after formation of bony callous) or disco-ligamentous lesions (protracted instability caused by inadequacy of fibrous union).

1. The Elements of Vertebral Stability

- Vertebral stability is ensured by the anterior column of discs and bodies, and by the two posterior columns of processes and articulations. It should be noted that these three columns fused at the axis. From the atlas to the occiput, only the two lateral columns remain.

- Horizontal stability at the level of the mobile segments is dependent upon bony buttresses (odontoid, uncinate processes, articular, spinous, and transverse processes) and on the intervertebral ligaments. It is clear that instability may be entirely ligamentary, as in some severe cervical dislocations and sprains, and thus poses difficult diagnostic problems. These anatomical structures are radiotransparent.

2. Theories of Spinal Instability

These are diverse. According to Nicoll (386) and Holdsworth (336, 337) instability is related to the disruption of the posterior ligamentary complex, in particular the interspinous ligaments. Rieunau and Decoulx (279) consider that it is due to the break-down of the posterior wall of the disc-body complex. For Camille (261, 411) a lesion of the middle vertebral segment is responsible for the instability (the posterior wall, with its attached ligaments, pedicles, articular processes).

3. Factors in Instability

These are multiple. They include:

- comminution of a fracture of the body, which prolongs the time of consolidation

- pinching of one or more intervertebral discs

- rupture of the interspinous ligaments (Fig. 107)

- breach of the posterior wall (Decoulx and Rieunau (279), Fig. 106). This is an anatomical concept represented by the smooth vertical alignment of the posterior borders of the intervertebral discs and vertebral bodies and their attached ligaments. On a lateral radiogram, it is the line running along the posterior border of the vertical bodies (Fig. 102).

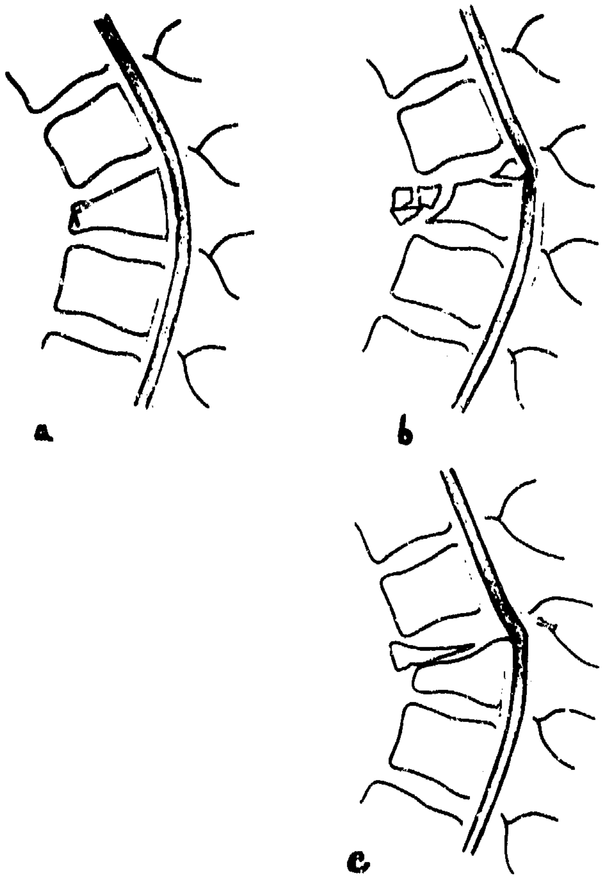


Figure 106. Pathological/anatomical classification, modified from Decoulx and Rieunau (279).

a) Anterior wedge fracture with intact posterior wall
b) Complex fracture with injury to wall of resistance and rupture of posterior wall
c) Fracture dislocation with rupture of posterior wall and intact wall of resistance.

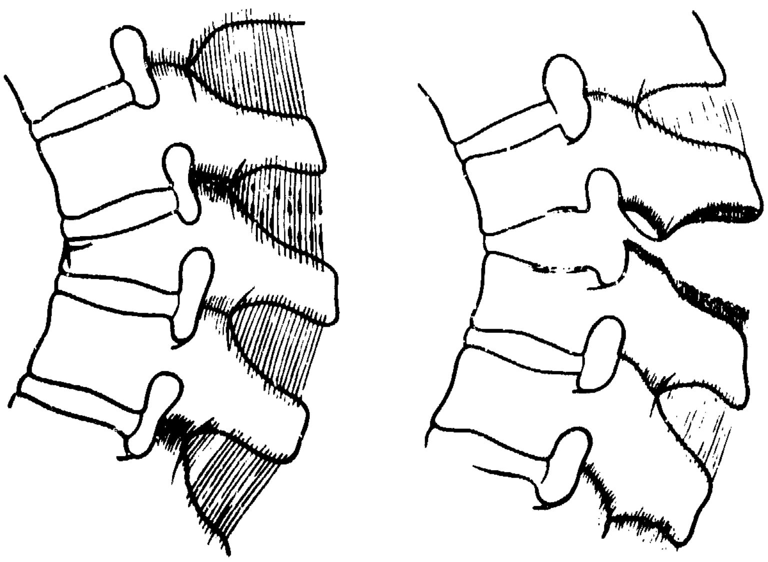


Figure 107. Sprain and tearing of interspinous and apophyseal ligaments in spinal trauma (after Watson-Jones, 448).

a) In stable fractures the interspinous ligament is usually intact
b) In unstable fractures the interspinous ligament is often torn.

The Wall of Resistance (294)

The architecture of the vertebral body comprises three systems of reinforcing arches; horizontal, vertical and oblique (Figs. 5 & 6). Thus, the anterior and medial part constitutes a zone of least resistance, susceptible to anterior wedge compression. In contrast, the very tight intersection of the trabeculae at the site of insertion of the pedicles (Fig. 5) increases the strength of the posterior part of the vertebral body, which acts as a "wall of resistance" for the nervous structures in the spinal canal. This protective wall (Fig. 6) includes the pedicular insertions and an intermediate zone that includes some depth of the posterior portion of the vertebral body. An injury to the wall of resistance can be accompanied by disruption of the posterior wall (Fig. 105), with separation of the pedicles. The fracture is then unstable. However, it may be isolated, and the fracture may be stable. Nevertheless, neural lesions can occur immediately or later, from encroachment upon the spinal canal and its contents. Thus, bursting or explosive fracture of a cervical body is an example of a stable fracture (because of the integrity of the anterior longitudinal and interspinous ligaments), yet disruption of the wall of resistance by the backward recoil of a fragment may be responsible for a later neurological lesion. Thus, in a frontal radiogram, the displacement of one or two pedicles (Figs. 103 & 104), from alignment with other vertebral pedicles indicates a fracture that is unstable anteriorly and posteriorly, and a lesion to the protective wall. In a lateral view the alignment of the posterior margin of the intervertebral ligaments is examined for evidence of a discontinuity between discs and bodies (rupture of the posterior wall with or without breach of the wall of resistance) and perhaps localised bulging of all or part of the posterior face of the vertebral body into the spinal canal (Fig. 105).

4. Radiological Signs of Instability

In this context the spine must be separated into two regions; thoraco-lumbar and cervical.

The Thoraco-lumbar Spine

In frontal views, the radiologist looks for several signs:

- divergence of one or two pedicles of a vertebra in relation to the alignment of the pedicles above and below. This is a rupture of the "spinal ring". There is unilateral or bilateral displacement of the posterior articulations. A fracture of the laminae may be detected (261)

- displacement of one spine from the line of the others

- increase in the distance between two spines compared with those above and below (lesion of the interspinous ligament)

- fracture of the laminae below L4.

In lateral views, the presence of one or more significant signs must be noted.

- rupture of the posterior wall (279, 336, 337, 386, 448)

- fractures of the pedicles or of the posterior articular processes

- comminuted fractures of the vertebral body

- divergence of the spinous processes.

The Cervical Spine

The same signs that indicate instability of the thoraco-lumbar spine are found at the cervical level. But here, the instability can be of ligamentary origin with very few bony lesions (dislocation, subluxation, severe sprain). These confirmatory signs of instability are sought in frontal and lateral X-rays.

Frontal View

There is an abnormal increase in the distance between two spines (dislocation), while this value is nearly the same throughout the normal cervical spine. A large deviation in the line of the spines occurs in cases of unilateral dislocation.

Lateral View

In lateral views it is possible to demonstrate:

- splitting of the articulations at one level, while they remain superimposed below. If there is rotation, an articular fracture should be looked for

- anterior or posterior displacement of a vertebral body of more than 3.5 mm above C4 or of more than 2 mm below C4

- exposure of more than 50% of an articular surface, or posterior widening of the interarticular line posteriorly

- angulation of more than 11° of a vertebral body with respect to the body immediately below

- widening of a disc space greater than that of the spaces above and below.

In some cases, the frontal and lateral views taken at rest do not reveal radiological signs of instability. These only appear during dynamic examinations, which must be carried out with the greatest caution in such cases.

5. Differential Radiological Diagnosis of Instability

In individual cases, this lies between:

- reversal of the physiological curvature of the cervical spine

- postural disturbance (flat or hollow back)

- an acquired false joint above a congenital, acquired or functional vertebral lock (arthritis)

- an unstable discoligamentary lesion. In this case, the angulation of the lateral cervical curvature disappears in hyperextension, and increases in hyperflexion.

It is necessary to avoid some pitfalls arising from functional anatomy, superposition, and poor alignment. It is absolutely essential to demand strictly frontal radiograms to appreciate deviations in the line of the spines, and perfect lateral views to avoid superimposition of the articulations.

In case of doubt, and to avoid any erroneous interpretation, fresh exposures are made, and complemented by oblique views and by frontal and lateral tomography.

5.5.2.2. Radiological Signs of Primary Lesions of Bones and Ligaments

Inspection of the detailed summary shows that these bony and ligamentous lesions can occur in more or less complex association or in isolation, and affect the vertebral body, the posterior arch, and the ligaments (40, 45, 51, 52, 166, 274, 339, 374).

Detailed Summary

1. The Vertebral Body
    a. Anterior Wedge Compression
    b. Comminuted Fractures
    c. Fracture Dislocations
2. Posterior Arch
3. Ligamentary System

1. The Vertebral Body

Several types of fractures exist; wedge compression (the most frequent, in all its forms), comminuted fractures, fracture dislocation which may be associated with injuries to the posterior arch, to the discs, or at remote sites (293, 397, 398, 448).

We shall follow the same plan in describing them all:

- the shape of the body

- the appearances of the end plates and angles

- the opacity and structure of the bony mass

- injuries of the posterior arch

- displacements and postural disorders

- associated lesions (of the disc, ligaments, and soft tissues)

- remote lesions.

Figure 108. Fracture of D11, characterised by wedge compression (ejection).

Figure 109. Fracture of D10 (ejection) - "dribbling" anterior corner.

Figure 110. Localised compression of upper surface of L5 (helicopter accident).

Figure 111. Same pilot as Figure 110, detachment of anterior corner of L5.

Figure 112. Fracture of D8/D9 (parachuting) with consolidated appearance (Gérard-Marchant).

Figure 113. Oscillation accident - Fracture of D7/D8.
D7 - damage to lower vertebral end plate
D8 - damage to upper vertebral end plate

a. Anterior Wedge Compression

Shape of the Body

Wedge compressions are the most frequent, lateral compression being less common. Anterior wedge compression is seen as a reduction in the height of the vertebral body localised in its anterior part (Fig. 108).

One or several vertebrae may be affected. Frequently, the same appearance of anterior wedge compression is seen in all fractured vertebrae. The lateral view, which is the most revealing, defines the degree of compression. In most cases, it is slight, but sometimes the height of the vertebral body is reduced to a quarter or one third. Frontal radiograms sometimes show widening of the vertebral body.

Lateral compression, more rarely isolated, is seen in most cases in association with an anterior wedge compression. In the anteroposterior view, the vertebral body shows an asymmetry of its height in the frontal plane.

Appearances of the Angles and Contours of the End Plates

The anterior contours are often irregular; in wedge fractures, the anterior angle projects beyond the vertebral margin. It is then said to "dribble" (Fig. 109). The line of fracture is rarely visible, which led Watson-Jones (448) to speak of fractures enclosed in compression. In many cases, the anterosuperior corner is torn away. The line of the fracture is then visible and is irregular or serrated. The anterior border of the vertebral body is deformed to an obtuse angle. Compression fractures are accompanied by disruption of the anterior part of the end plate. In 75% of cases, only the upper vertebral surface is affected. With violent trauma, it is not uncommon to observe injury to two vertebral end plates. Isolated injury to a lower end plate is seen in special forms of trauma; hyperflexion with the head down, or accidents involving severe vibrations of the induced oscillatory type (Fig. 113). Most often, fractures limited to the inferior vertebral plateau are seen in pathological fractures (metastases, for example) without any severe trauma.

Density and Structure of the Bony Mass

In fractures examined shortly after the trauma, the changes in the density or structure of the bone substance are not always large.

In some cases it is possible to see a more or less consolidated appearance in a vertebra with a discrete anterior wedge compression. This condensation is always at the site of the fracture. When a vertebra with normal morphology shows condensation which may be central and very localised, it corresponds to the picture described by Gerard Marchant (283) under the term "latent fracture of the first degree" (Fig. 112). This very special type heals very rapidly (often without the application of a cast). The condensation usually disappears in the course of 3-4 months.

Injuries to the Posterior Arch

The posterior wall is intact but lesions of the posterior arch are sometimes seen. They most often involve the transverse processes.

Displacements and Postural Disorders

In simple compression with an intact posterior wall there is no vertebral displacement, and no immediate or delayed disturbance of posture. In severe compressions, the very pronounced effect on posture and stability may require intervention to prevent painful sequelae.

Associated Lesions

In anterior wedge compressions the discs are generally unaffected, but in some cases the nucleus pulposus may break through the end plate on which it is supported, and a break in the surface, with relatively clean edges, can be seen (Fig. 114).

Lesions of the disc can be associated with major compression. The disc underlying the fractured vertebra is most often affected. Sometimes, these lesions coincide with a simple rupture of the vertebral plateau. On the lateral X-ray the end plate shows as a line broken in its middle or anterior part.

Lesions of the disc, which very rarely occur in isolation, appear as a simple narrowing of the disc-space without bony lesions. To confirm that this is an acquired characteristic, technically good radiograms made before the trauma must be available. A disc thus injured never heals. This disc lesion leads sooner or later to arthritis. Finally, a disc underneath a fracture, which is of normal thickness just after the accident, can diminish in height during the following weeks. By discography of the discs above and below the fracture, Goutalier and Bernageau have shown that injury to the disc and ligaments is correspondingly greater when the fractures of the body are smaller and more anterior.

Figure 114. Fracture of L1 with breach of upper vertebral end plate (clear notch). Appearance 1½ months after the trauma (ejection).

Figure 115. Sagittal fracture of L3, parachuting accident in a forest.

Figure 116. Fracture of L1 with dislodgement of the anterior corner. Narrowing of the D12/L1 interface and rupture of the posterior wall (parachuting).

Figure 117. Fracture - dislocation of L1 with paraplegia (parachuting).

Figure 118. Tomogram of a pilot after ejection (night landing in mountains). Fracture of L1 with damage to the wall of resistance and the posterior wall.

Figure 119. Gliding accident - Stall at low altitude.

Remote lesions are frequent in major trauma and include:

- reflex gaseous distension of the colon

- other traumatic lesions (fractures of the limbs, of the skull, of the thorax).

b. Comminuted Fractures and Fracture Dislocations

In a comminuted fracture, the vertebral body is broken into several fragments, which are sometimes dislodged. In fracture dislocations, the main fracture line passes obliquely from back to front and from above downwards through the posterior arch and the vertebral body.

Shape of the Body

In a comminuted fracture, the shape of the body is profoundly changed. There is considerable wedge compression, which produces an acute angulation of the spine at this level. Fragments are extruded anteriorly and laterally. In frontal views, the vertebral body is widened, sometimes asymmetrically. From the lateral aspect, the anterior fragments clearly project forward, while the roughly trapezoidal posterior fragments bulge backwards (Figs. 116 & 117).

In fracture dislocation, the fracture line continues that of the break in the posterior arch, traversing the body in a direction which is most often oblique from behind forwards and from above downwards, and generally passes through the upper third of the body. It divides the injured vertebra like the fracture of a long bone, into two or more fragments; upper and lower. This description applies to the picture most frequently seen, but in some cases of violent and complex trauma, where the forces act simultaneously in all three axes, any attempt at classification is difficult or even useless, because of the impossibility of detailed and prolonged examination of the fracture sites without major risk to the casualty.

A sagittal fracture of the vertebral body (described for the first time by Guilleminet (330)) results from trauma associated with hyperflexion and more or less complex rotation. This picture is rarely seen; the vertebral body is split by a vertical line running from the interspace immediately above the fractured vertebra to that immediately below. This fracture is often accompanied by injury to the interspinous ligament (295, 448) (Fig. 115).

In the last 10 years we have encountered this clinical form 11 times, the majority in parachutists or pilots after ejection who have had difficult landings, mostly in forests.

Shape of the Fragments

The contours of fragments from recent fractures are clean.

Density and Structure of the Bony Mass

Although quite often normal, this can be modified by a homogeneous consolidation which usually disappears later than in stable fractures.

Injuries to the Posterior Arch (Figs. 118, 123 & 124)

In a comminuted fracture, because of the fragmentation of the vertebral body and gross displacement, the posterior arch is always damaged; in particular, the articular processes are dislocated or fractured. In some cases injury to the wall of vertebral resistance is severe. It appears as a bulge in the posterior line of the vertebral bodies with a well defined decrease in the posterior height, associated with slight backward displacement of the fractured vertebra (Fig. 118). This picture is seen especially at the level of the thoracic vertebrae between D4 and D8 and, less frequently, at the lumbar level. In all cases, the spinal canal is narrowed to some degree. A stenosis of more than one third of the anteroposterior diameter, compared with that of the vertebrae above and below, leads to potential or actual compression of nerves, and demands corrective treatment (367b).

In a fracture dislocation, the oblique fracture line runs through the body and the posterior arch. It displaces the articular processes and damages the pedicles, the laminae or one or other of the posterior attachment and fixation systems. In both these types of fracture, displacements and disturbances of stability are severe.

Most orthopaedic surgeons agree on the value of measuring the kyphosis, an important parameter in the assessment of the fracture site. Several techniques can be used for this measurement;

- determination of the angle formed by the superior and inferior plateaux of the injured vertebra

- determination of the ratio between the heights of the anterior and posterior borders of the fractured vertebra

- tracing the axis of the spine: the line joining the anterior borders of the vertebral bodies describes a regular curve of large radius. The angle made by this line when there are one or more spinal fractures is an accurate measure of the compression; that is, the degreee of gibbosity.

This last method is preferable, because it is the only one that can be applied in multiple trauma. It takes account of the frequent and variable compensatory changes in the discs. An increase of more than 15° in the thoracic kyphosis and of more than 10° in scoliosis are the upper limits of long-term tolerance (367b).

Associated Lesions

The intervertebral discs are always damaged in comminuted fractures and fracture dislocations. Rupture or destruction is seen as total or partial collapse. Generally, it is the disc below the fractured vertebra that is damaged, but in comminuted fractures it is not uncommon for the discs above and below to be involved in the trauma.

Exceptionally, in thoracic fractures (above D10), a symmetrical or asymmetrical paravertebral shadow is evident, which represents a haematoma. Of variable size, it often regresses very rapidly (15-20 days) (Figs. 121 & 122). Its significance is difficult to determine: haemorrhage into the soft tissues around the spine? Associated fracture of a transverse process? The interspinous ligaments are torn, and damage to the soft tissues is severe.

Lesions of the discs and the interspinous ligaments, which do not heal spontaneously, have grave implications not only for the later history of the fractures and their sequelae, but also for the immediate course. They can be a factor in secondary mobilisation after reduction.

Remote Lesions

In these cases of major trauma, the casualty usually has several fractures (limbs, skull, rib cage) or lesions of the thorax or of the abdomen.

2. The Posterior Arch

Detailed Summary

a. Isolated Fractures of the Posterior Arch
   Fractures of the Spinous Processes
   Fractures of the Transverse Processes
   Fractures of the Articular Processes

b. Fractures of the Neural Arch
   Fractures at the Level of the Pedicle
   Fractures of the Laminae
   Fractures of the Isthmus

A distinction is made between isolated fractures of some component of the posterior arch, and those associated with stable or unstable lesions of the vertebral body.

a. Isolated Fractures of the Posterior Arch

These include fractures of the spinal, transverse, and articular processes. The spinous and transverse processes, normally protected by their muscle covering, are vulnerable to direct impact or to excessive effort with violent contraction.

Fractures of the Spinous Processes

These generally result from direct trauma. Most commonly, they are at the level of the cervico-thoracic or thoraco-lumbar junctions. The spinous processes of D1, D2 and L1 are most commonly affected. They are accompanied by displacement of the distal fragment, and by swelling of the soft tissues denoting the presence of a haematoma. More or less extensive abrasions of the skin frequently attract attention. The line of the fracture passes through the weakest point of the spinous process, usually vertically and through the middle. The margins of the line are sharp and irregular, and there is sometimes an intermediate fragment.

Fractures of the Transverse Processes (Figs. 125 & 126)

These fractures, which are more frequent in the lumbar than in the cervical region, most commonly result from direct trauma or from violent muscular effort. The line of the fracture usually involves the narrow part of the process. It may be single, but more often involves several transverse processes on the same side. In violent trauma, bilateral fracture lines may be seen. The distal fragment is generally displaced downwards, its movement being produced by contraction of the lumbar muscles. Swelling of the psoas is due to a haematoma. In very rare cases, the transverse line of fracture forms an extension of a fracture of the posterior arch.

Figure 120. Complex fracture of L4-L5 with neurological injury (cauda equina syndrome), traumatic lesions (perforation of bladder) and fractured pelvis.

Figure 121. Haemotoma visible on the face of the vertebra. Stable fracture of D9 (parachuting accident).

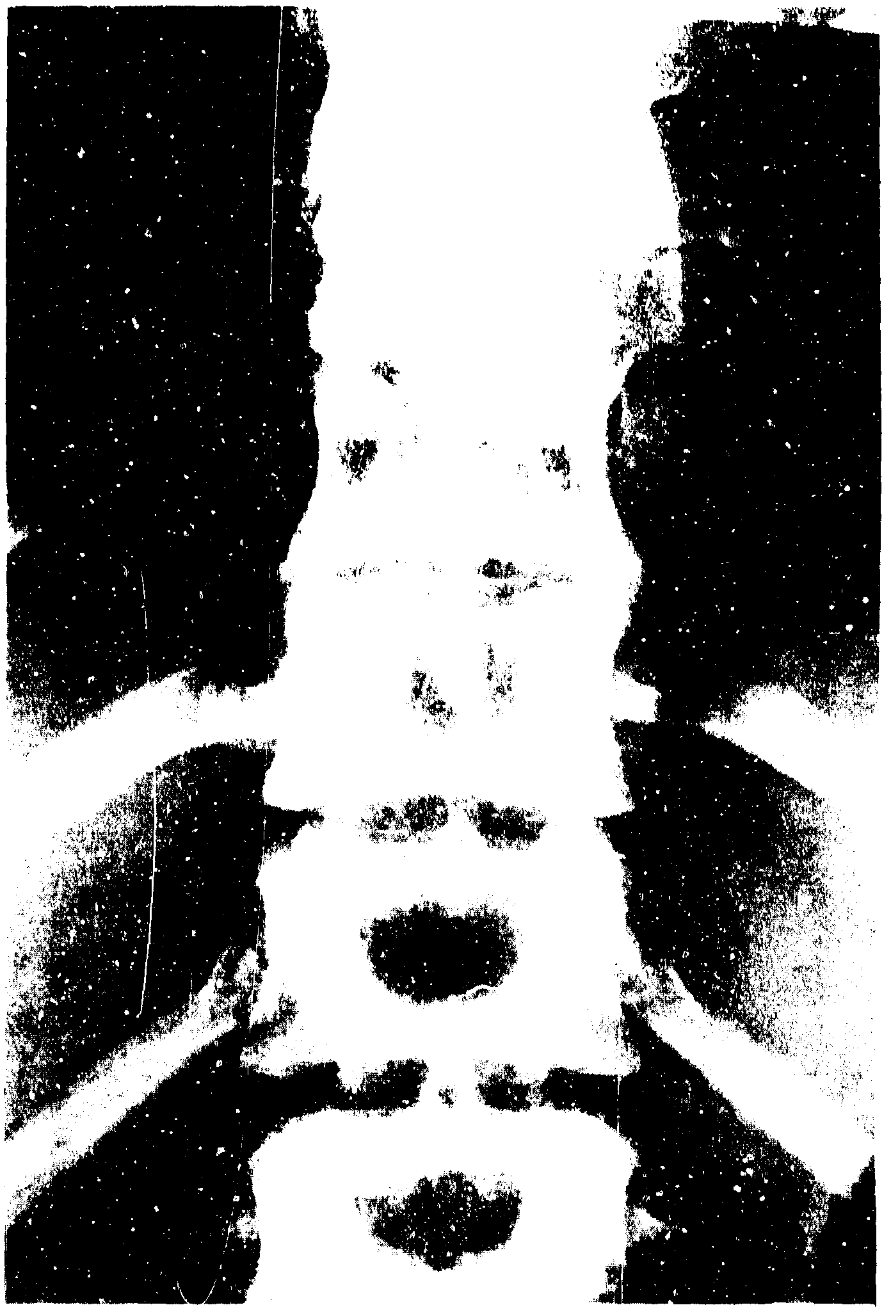


Figure 122. Same case as Figure 121. Stable fracture of D9
Regression of haematoma after 10 days.

Figure 123. Crash - Fracture of left pedicle of L1.

Figure 124. Crash; same pilot as Figure 123. Fracture of body of L1.

Figure 125. Crash of single-engined light aircraft. Fractures of left transverse processes of L1, L2 and L3.

It is notable that patients with fractures of the lumbar transverse processes suffer greatly. Violent, continuous pains, which are aggravated by movement or by coughing, explain why the casualty is intolerant of contact with the examination table. The X-ray plates should be of very low contrast, but in establishing the exposure, account must be taken of the presence of gaseous distension of the abdomen. If the plates are overexposed, fractures of the transverse processes will not be seen.

Fractures of the Articular Processes

These are very uncommon, usually occur in isolation and most often affect the cervical column. When they are in the thoracic or lumbar spine, they are usually associated with comminuted fractures.

b. Fractures of the Neural Arch

These affect the pedicles, laminae and isthmus. Most frequently, they are associated with unstable fractures of the vertebral body.

Fractures of the Pedicles

These rare fractures appear after direct impact (for example by a bullet), where the line of fracture passes through the posterior arch and damages the pedicle. Their development almost always releases the vertebral body from its posterior attachments. This is the case in detachment of the pedicle in complex unstable fractures with rupture of the posterior wall and the wall of resistance.

Fractures of the Laminae

Isolated fractures of the laminae, which are very rare, occur after a direct impact. They are usually accompanied by fractures of the spinous processes and dislocation of the processes. The fine, irregular fracture line is easily distinguished from a congenital fissure (dehiscence of the posterior arch). If the lesion is bilateral, the vertebral body is displaced forwards. These fractures are most often associated with complex fractures of the anterior arch and disruption of the posterior arch.

Fractures of the Isthmus

The isthmus, a simple bony bridge joining the superior and inferior articulations is not, as is commonly believed, a constitutionally weak point of the vertebral arch. Knowledge of spinal dynamics shows that, because of the different distribution of forces between the anterior and posterior columns, the vertebral body will be compressed before the isthmus or the lamina is fractured. A picture of spondylolysis or of spondylolisthesis is almost always congenital. For the observation of lesions of the isthmus in cases of localised trauma the following criteria must be met:

- frontal examination of the trauma site by the proper techniques (including standard views and tomograms)

- posterior views of the trauma showing an irregular fracture line at the level of the isthmus.

Most experts in forensic medicine consider that spondylolysis and spondylolisthesis are practically never of traumatic origin. It goes without saying that some forms of trauma (bullets, for example) which damage the posterior arch can produce spondylolisthesis as part of a complex radiological picture which includes multiple traumatic lesions.

The association of unstable fractures of the body with fractures of the components of the neural arch is well illustrated by Roy Camille's concept of damage to the middle vertebral segment. In the numerical notation devised by Louis (367), complex fractures are unstable if the sum of the elements is greater than 2. This author assigns one point to complete dissolution of continuity between the body and the articular process, and 0.5 point for incomplete disruption of vertical stability in a column of three vertebrae, or complete rupture of horizontal stability over two elements.

3. Ligamentary Lesions

Some indirect signs of the presence of ligamentary lesions may be re-iterated. Rupture of the interspinous ligament appears in frontal views as an increase in the distance between two spinous processes. This should not normally be more than one and a half times that of the space above and below. In lateral views it is seen as separation between two spinal processes.

The Anterior Longitudinal Ligament

- Rupture is likely in wedge compression fractures with displacement of the anterior superior corner.

- Rupture is invariably present in displacement fractures of the anterior inferior corner of the axis. Moreover, such fractures are unstable in extension.

Figure 126. Difficult landing after ejection. Fractures of right transverse processes of L1 and L2.

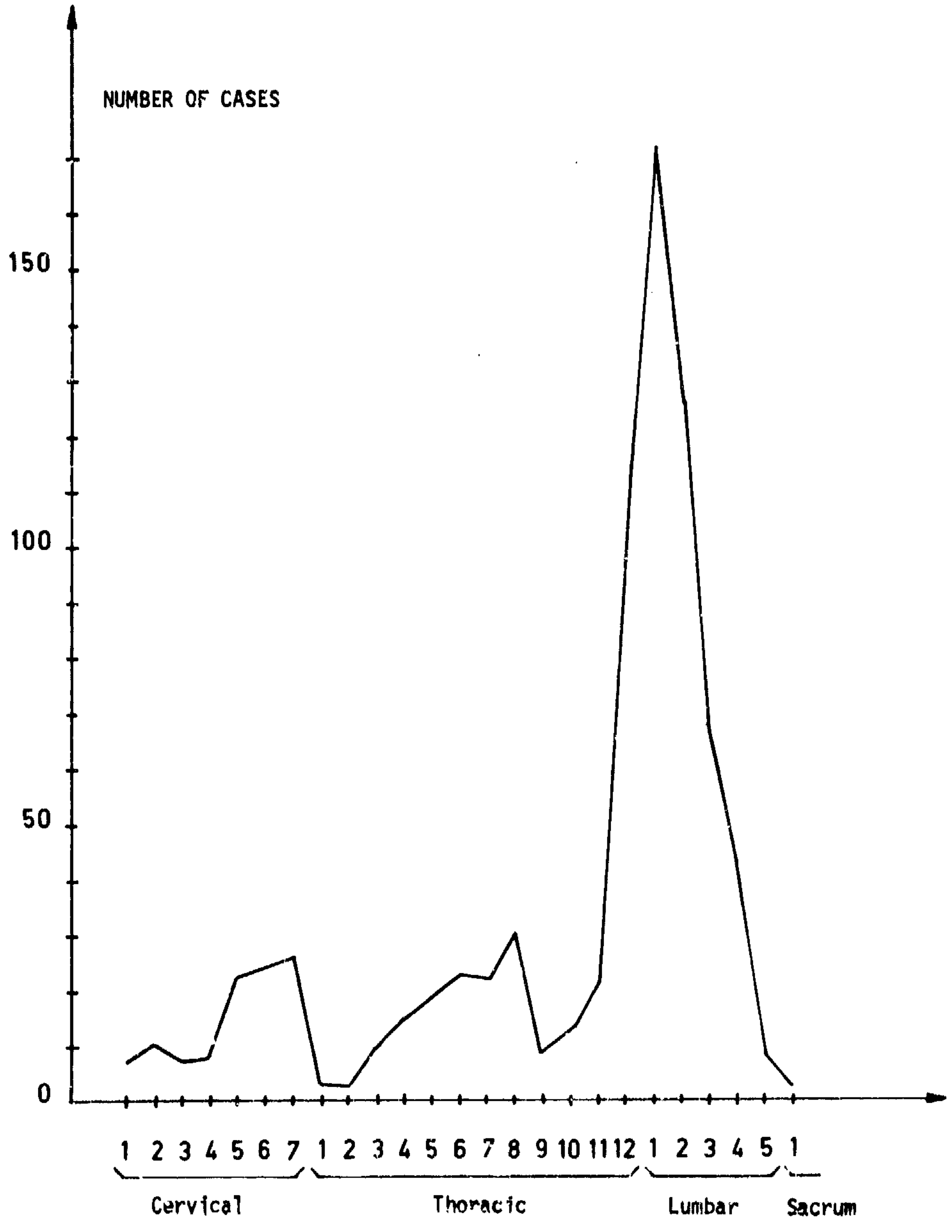


Figure 127. Statistics of spinal fractures.
(806 cases seen and treated at the Dominique Larrey, Begin and Percy Hospitals).

TABLE 5.17

Site of Injury	SERIES I 1960-66	SERIES II 1967-79	Total	% of Total
C1	3	4	4	0.86
C2	4	6	10	1.24
C3	2	5	7	0.86
C4	3	5	8	0.99
C5	12	10	22	2.72
C6	13	11	24	2.97
C7	12	14	26	3.22
D1	1	2	3	0.37
D2	1	2	3	0.37
D3	6	4	10	1.24
D4	7	8	15	1.86
D5	9	10	19	2.35
D6	11	12	23	2.85
D7	10	12	22	2.72
D8	16	14	30	3.72
D9	4	5	9	1.11
D10	6	7	13	1.61
D11	11	10	21	2.60
D12	57	58	115	14.26
L1	89	81	170	21.09
L2	69	57	126	15.63
L3	36	31	67	8.31
L4	25	19	44	5.45
L5	4	5	9	1.11
S1		3	3	0.37
Total	411	395	806	

The Posterior Longitudinal Ligament

Rupture is generally certain in any severe case of injury to the posterior wall and when there is an anterior subluxation in the cervical region. The latter is essentially characterised by the appearance of signs in flexion which disappear in extension.

5.5.3. Classification of Spinal Fractures

The complexity of fractures and dislocations of the spine explains the great diversity of classifications of fractures of the vertebral column. Recently, several authors have stressed the need to differentiate anatomical and radiological types according to their causal mechanism (extension, flexion, extension and rotation, flexion and rotation, lateral flexion).

For our part, we consider that this new classification does not serve the proper needs of therapeutic efficacy. For the present study we shall follow the classical scheme, and shall consider in turn thoraco-lumbar fractures and those in the cervical region. Finally, we shall compare stable and unstable fractures.

Two different sets of statistics are available (Table 5.17). The first comes from spinal fractures observed and treated in military hospitals; the Percy Hospital at Clamart and the Dominique Larrey Hospital at Versailles, from 1960 to 1966 inclusive. Three hundred and seven casualties with four hundred and eleven fractures were investigated.

The second category contains all cases seen at the Begin Military Hospital from 1970 to 1979 inclusive (casualties seen at an early stage and reviewed regularly) and all cases sent for expert opinion and for reappraisal. Eight hundred and six spinal fractures were seen in six hundred and two subjects, drawn from the statistical records of the Orthpaedic Surgery, Rheumatology, and Radiology Departments. Among these injuries of very varied origin (road traffic accidents, sporting accidents, ejection after aircraft accidents, parachuting) we found the following distribution in decreasing order of frequency (Fig. 127):

- thoraco-lumbar junction (D11 to L2)
- lumbar column
- middle and lower thoracic column (D5 to D10)
- lower cervical column (C5 to C7)
- upper thoracic column (D1 to D4)
- upper cervical column.

Increased severity of the trauma explains the large number of casualties having multiple fractures (293, 375) (Tables 5.18 & 5.19). Multiple fractures occurred in 21.02% of cases in Series I and 25% of cases in Series II, which gives ground for systematic radiography of the entire vertebral column in all moderately severe cases of trauma and particularly after aircraft accidents.

TABLE 5.18

Series I (1960-66 inclusive)

Number of Fractured Vertebrae	Number of Casualties SERIES I	Total of Vertebral Fractures
1	240	240
2	45	90
3	12	36
4	6	24
5	3	15
6	1	6
Total	307	411

TABLE 5.19

Series II (1967-79 inclusive)

Number of Fractured Vertebrae	Number of Casualties SERIES II	Total Vertebral Fractures
1	221	221
2	54	108
3	10	30
4	7	28
5	2	10
6	1	6
Total	295	393

TABLE 5.20

Different Distributions of Spinal Fractures in Aviation Medicine (from Delahaye et al (52))

Type of Trauma	Commonest Sites	Less Frequent Sites	Unusual Sites
Aircraft crashes	Thoraco-lumbar junction; D10-L2	High or mid thoracic	Low lumbar
Helicopter crashes	Thoraco-lumbar junction; D10-L2	Low lumbar	High or mid thoracic
Parachuting	Thoraco-lumbar junction; D10-L2	High or mid thoracic; Low lumbar	C5-C7
Ejection	Thoraco-lumbar junction	High or mid thoracic	Low lumbar

From the study of multiple fractures in these two sets of statistics, it is possible to observe the frequency of some associations:

- injury to the D12/L1 junction, and of D11 and L2

- the large number of multiple lumbar fractures

- association between fracture of the D12/L1 junction and of a middle (the most frequent) or upper thoracic fracture

- the high incidence of multiple injuries to the transverse processes.

Table 5.20 gives the distribution of fractures of the spine in aviation medicine, as shown in the first edition of this monograph. The many casualties observed since that edition, and the many cases examined and reassessed for fitness or for compensation, allow us to confirm that this picture remains valid in the majority of cases encountered in aviation. This analysis once more confirms the value of a comprehensive examination of the spine.

5.5.4. Radiological Studies of Fractures of the Thoraco-lumbar Spine

These represent 85% of spinal fractures seen in general practice, and perhaps even more in aviation. They are grouped between D6 and D8 on the one hand, and D11 and L4 on the other. The majority of them are stable. Multiple fractures represent about 15% of cases.

5.5.4.1. Stable Factures

Different anatomical and radiological types can be distinguished: silent compression fracture of the vertebral body, marginal fracture, anterior wedge fracture, single fracture of the posterior arch (274, 277, 283, 293, 448).

1. A silent fracture of the vertebral body must be carefully looked for, because it can pass unnoticed. It is visualised in lateral views (standard and tomographic) as a very small angulation in the anterior face of a vertebral body, sometimes with a single band of increased density in the equatorial region of the body (form of G. Marchant).

2. Marginal Fractures

Marginal fractures almost always involve the upper end plate of one or more adjacent vertebrae.

3. Anterior Wedge Fractures

We have already described the signs and different gradations of anterior wedge fractures.

The differential diagnosis of wedge compression fractures in aerospace medicine requires a thorough knowledge of the morphological variations of the vertebral body, and of various developmental anomalies which must not be confused with traumatic changes or their after effects. Actually, this is a relatively simple intellectual exercise. We shall study in succession:

- the morphological variations which can cause confusion with a vertebral fracture

- changes due to a developmental disorder of the vertebral body or to the disc-vertebra complex (anterior wedging, retromarginal herniation, Schmorl's nodules).

Morphological Variations

Vertebrae can present a number of morphological variants. The most common is represented by vertebrae with a wedge shape of congenital origin, which may be thought to have a traumatic aetiology.

Definition of a Wedge Shaped Vertebra

The concept of a wedged vertebra has not always been clearly stated, and its definition varies with different authors. It is necessary to distinguish between:

- the true wedged vertebra of traumatic origin

- the vertebra with a wedge shaped aspect.

Dubouloz, Legre, Merjanian and Serratrice (304), in a statistical study of vertebral bodies with a tendency to be wedge shaped, used as a criterion differences of height greater than 2 mm on one side compared with the other in the frontal plane. In lateral views, the difference between the anterior and posterior borders should be equal to or greater than 3 mm for L1, and 2 mm for the other vertebrae. These numerical values can be accepted as the criteria for a vertebra with a tendency to wedging. We consider that only the lateral view has any real value in these determinations.

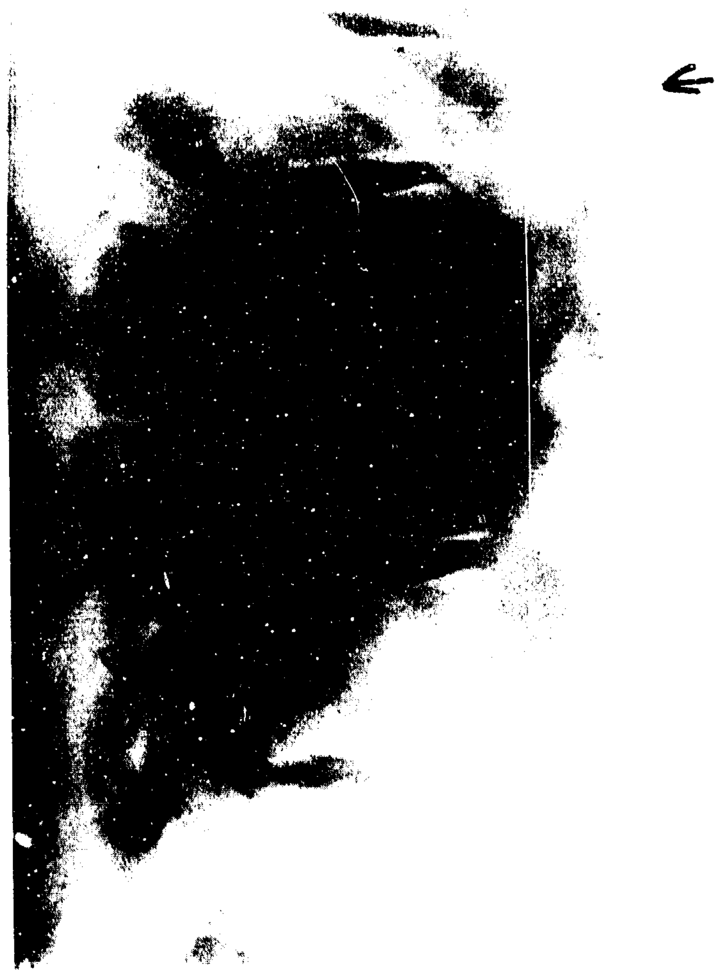


Figure 128. Wedge deformation of D7.

Figure 129. Wedge deformations of D12 and L1.

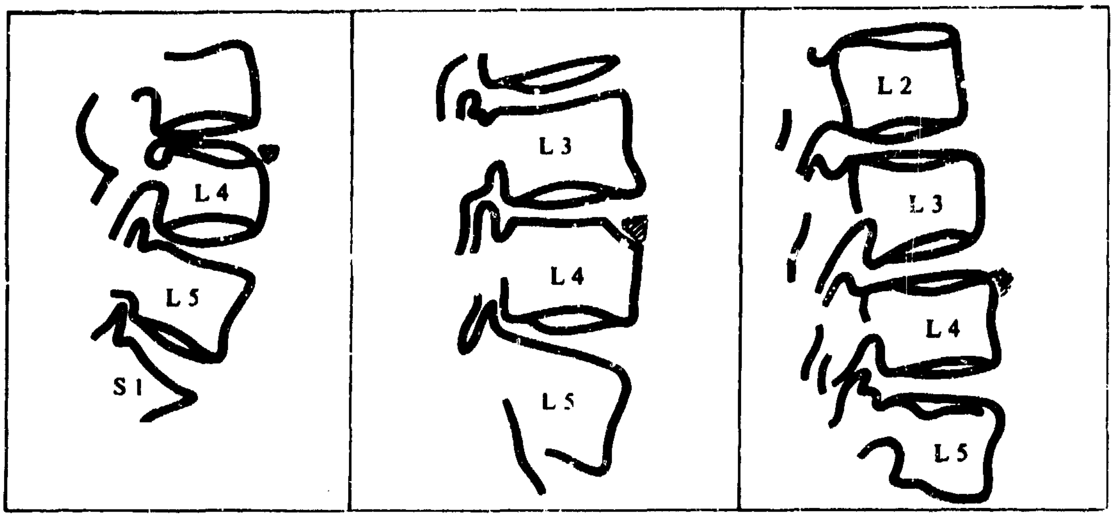
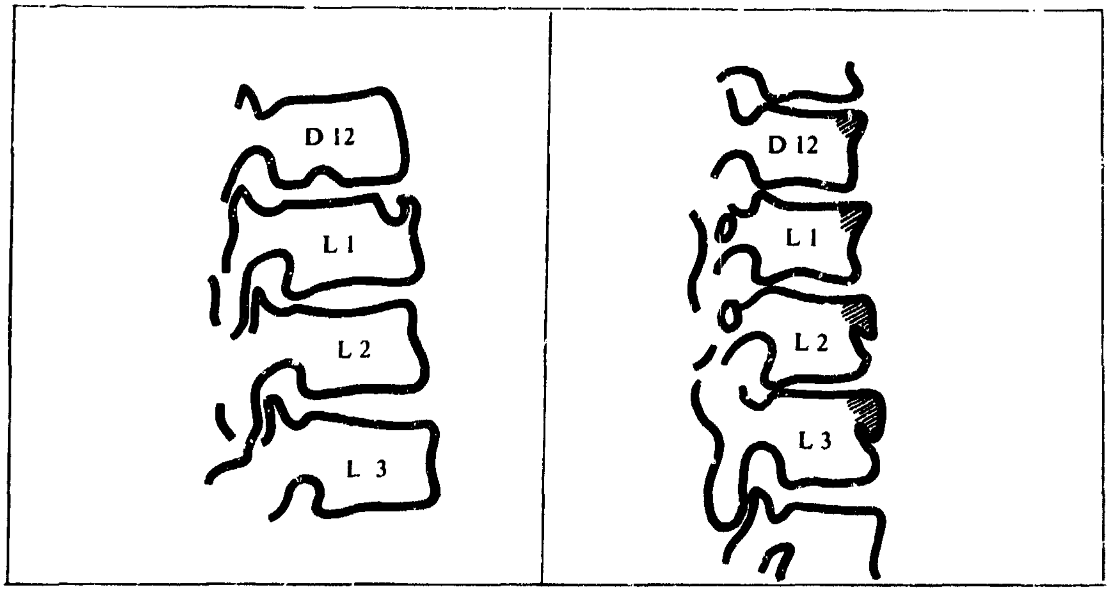


Figure 130. Diagnosis of anterior corner syndrome (after Decoulx).



Anterior retromarginal hernia

Multiple recent fractures

Figure 131. Anterior retromarginal hernia and multiple recent fractures.

In addition to these numerical data, it is appropriate to recall, with de Seze and Djian, that a vertebra of wedge aspect has regular, uneroded corners, without change of structure or of density. Such a vertebra is usually the result of a congenital anomaly. Despite these apparently precise defintions, it is quite evident that to confirm the acquired nature of a compression in doubtful cases, account must be taken of:

- a comparative examination of films taken before and after the accident

- the results of frontal and lateral tomograms of the suspect vertebra.

The medico-legal implications are obvious.

Vertebrae with Wedge Shaped Aspect (52, 264, 287, 288, 304)

These morphological variants certainly exist, and are frequently encountered in daily practice. Brocher stresses that the thoracic vertebrae always have a very slight wedge shaped form and that this is entirely physiological.

These wedge vertebrae are found selectively at the centres of physiological curvature:

- D6 for the thoracic column

- D12 and L1 for the thoraco-lumbar junction.

A proper knowledge of these facts is of fundamental importance in the diagnosis of traumatic wedge compressions in the aviator or the parachutist, because these zones represent the elective sites for lesions (Figs. 128 & 129). Errors of omission or commission should be scrupulously avoided, and we place stress upon the integrity of the structure and the very small reduction in the height of vertebrae with the wedge tendency. Our task is always made easier in the aviator by the existence of a radiological reference dossier. The differential diagnosis poses no essential problem in practice.

Changes Due to a Disorder in the Development of a Vertebral Body and the Disco-Vertebral Complex

These morphological changes of a pathological nature present the radiologist with diagnostic problems appreciably more difficult than those of the wedge shaped variants previously considered. In fact, knowledge of the embryclogy and appearances of the vertebral body will prevent errors of commission. According to Decoulx, the differential diagnosis is easy, but he nevertheless stresses that mistakes are frequently made, even by experienced radiologists. Accordingly, three types of lesions should be studied:

- a failure of union of the vertebral corners in the adult

- anterior retromarginal herniation (de Seze and Rotes-Querol)

- the sequelae of epiphysitis.

The Absence of the Union of the Vertebral Corners in the Adult ("Paradiscal Defect")(52)

This extremely common abnormality has been described in the literature under the names:

- persistent spinal apophysis

- anterior paradiscal defect

- vertebral osteochondrosis desseicans of the adult (Galiand)

- persistence of the epiphyseal plates.

According to Schmorl and Junghans, the term vertebral epiphysitis is incorrect, because it refers to the marginal ring. On lateral views in infants, a clear line is often seen at the site of insertion of one or more vertebral angles.

The vertebral corners then appear as small, rounded triangular fragments, separated from the vertebral body (Fig. 130). In children, these appearances are normal, because fusion occurs physiologically at about the age of 21-22 years. Their persistence in the adult indicates a disorder of development which has prevented normal union.

The separation of the fragment from the vertebral body is usually complete, but sometimes incomplete. The most common site of the change is the anterior superior corner of the vertebral body (L1, L2 or L3), and the anterior inferior corner is rarely affected. The free vertebral fragment is separated from the body by a clear regular straight line, in contrast with the serrated edges of marginal fractures (Figs. 131 & 132).

Whereas the "paradiscal defect" will remain unchanged without tendency to union, the consolidation of a marginal fracture is accompanied by a most characteristic deformity; an irregularity in the curvature of the anterior face of the vertebral body ("unhooking").

Figure 132. Anterior corner of L4.

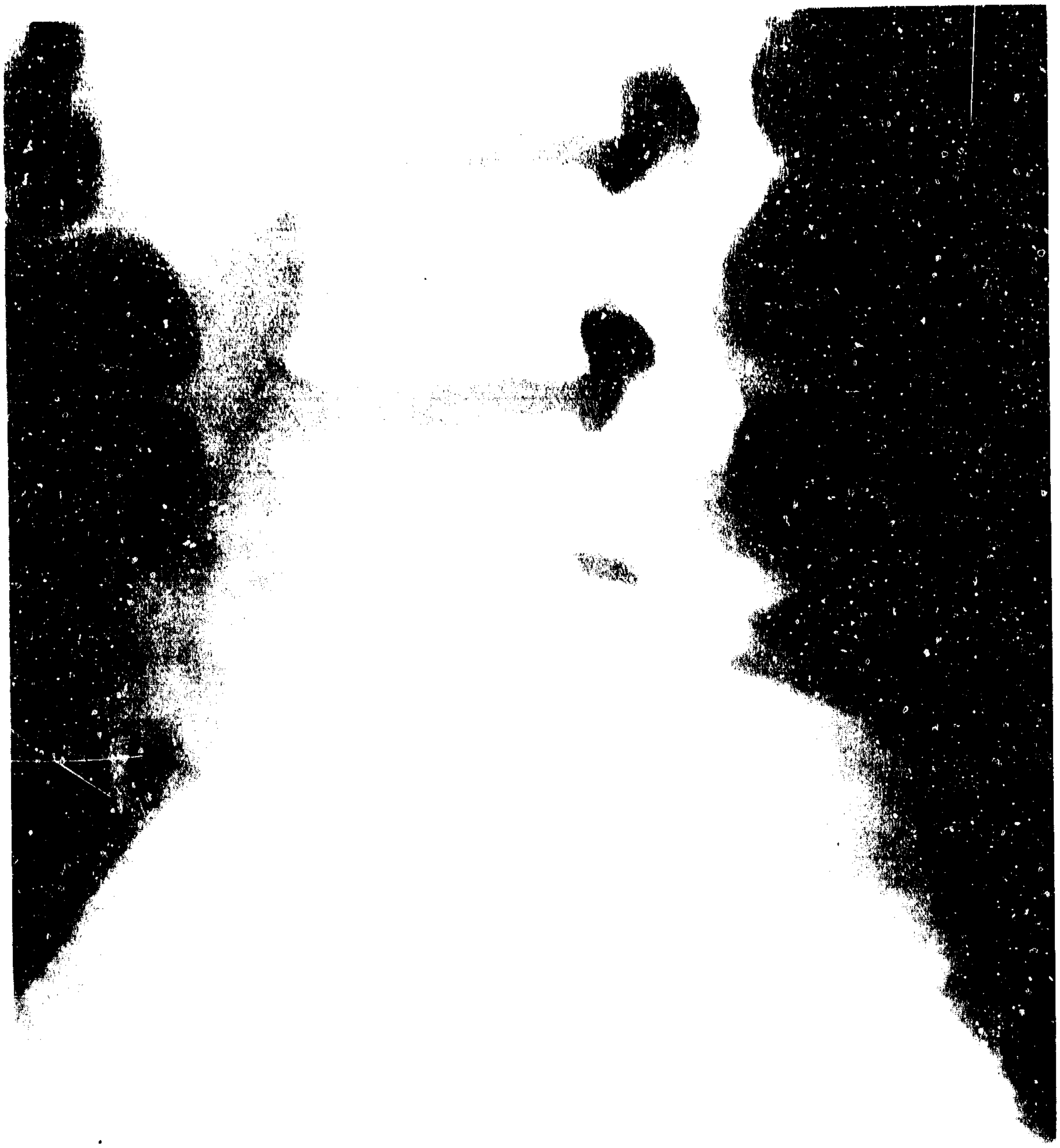


Figure 133. Anterior corner of L4.

It is rare for the detached corner to fit exactly into the contour of the vertebral body. It is either small, atrophied or even punctate, or else too large because of excessive growth, and overlaps the vertebral outline. The loose anterior corner may be associated with the lesions of the after-effects of Scheuermann's disease (vertebral epiphysitis). The body of the vertebra usually retains its normal shape, but it may be wedged posteriorly.

Many authors believe that this abnormality, even in isolation, weakens the adjacent disc, and thereby induces premature degeneration. We have been able to follow such lesions, confined to L1, L2 or L3, which did not result in the rapid development of arthritis.

In an injured person, this absence of fusion sometimes leads to errors of commission. However, the radiological characteristics of the abnormality are easily recognised. In different series of cases drawn from current practice or from aviation medicine, we have observed this anomaly on several occasions. In one very particular case, a detailed examination of the radiological dossier of the pilot of a conventional propellor driven aircraft allowed the diagnosis of a fracture previously made in another country, to be confidently reversed. We must stress the importance of a rigorous technique in taking the lateral X-ray. Even a small degree of rotation leads to the superimposition of the vertebral body and the anterior corner, giving the illusion of an underlying fracture fragment. To eliminate any question of interpretation in such a case, tomography provides irrefutable proof of the nature of the anomaly, by demonstrating the straightness of the breach of continuity, the smoothness of the contours, and the structural integrity of the detached fragment. Examination of reference X-ray plates is always very useful.

<u>Anterior Retromarginal Hernia</u> (Fig. 134)

de Seze and Rotes-Querol (421, 422) have described, under the name of anterior retromarginal hernia, a very characteristic notching in the upper surface of a thoracic or lumbar vertebra.

This anomaly is easy to diagnose. In lateral views, it slopes gently backwards and falls sharply in front. It is surrounded by a zone of increased bony density.

In the frontal view, it has the appearance of a large dome or raised cupula. The notching may be accompanied by a generalised decrease in the height of the intervertebral disc. There is sometimes an osteophyte in front of the vertebral margin.

According to de Seze (421), this change is not of traumatic origin, but always results from a dystrophy of growth. It generally occurs at the anterior site of least resistance of the vertebral spongiosa, which slopes downwards and forwards. This anterior retromarginal hernia, which is a variety of intraspongiosa hernia is often seen in Scheuermann's disease and its sequelae. It is usually accompanied by other characteristic signs of the disease, but it is possible to find an isolated retromarginal hernia (363). Radiological examinations (standard and tomography) are enough to confirm the diagnosis and to eliminate that of a fracture, which is sometimes made.

<u>The Sequelae of Epiphysitis of the Scheuermann Type</u> (278, 319)

These are responsible for wedge deformity, and for irregularity and lamination of the vertebral plateaux. However, there is no increase in the density in the mass of the vertebral body, nor deformation of the anteriosuperior angles.

<u>Isolated Fractures of the Posterior Arch</u> (429)

We have described their signs and symptoms in the consideration of basic principles.

Fractures of the laminae are stable above L4. They can be difficult to demonstrate on the standard X-ray when the posterior arch is seen obliquely, but careful adjustment of the beam can provide a perpendicular view. Three-quarter views and tomographic sections facilitate the diagnosis and reveal the fracture lines.

Fractures of the transverse processes sometimes pass unnoticed. They often involve several transverse processes on the same side. Swelling of the shadow of the psoas, indicating retroperitoneal haemorrhage with the possibility of traumatic renal injury, must be sought when the fracture affects the transverse processes of L1 or L2 (293, 369) (Figs. 125 & 126).

Isolated fracture of the spinous process is rare in the lumbar spine (it results from direct impact, or as a Chance fracture by lateral flexion).

5.5.4.2. <u>Unstable Fractures</u>

These are less common than the preceding ones, and represent 8% of the total fractures of the thoraco-lumbar spine seen in aviation. They are more serious, because the victim is liable to suffer neural damage (paraplegia, cauda equina syndrome). These lesions arise during the trauma, as secondary complications (premature mobilisation), or as sequelae (reduction in the diameter of the spinal canal from bone lesions or disc herniation, decompensation with postural disturbance; kyphosis increased by more than 15° or scoliosis by more than 10°).

Figure 134. Lumbar column - retromarginal hernia associated with anterior corner.

Figure 135. Anterior retromarginal hernia of L2.

Figure 136. Compression fracture of L1 with damage to the posterior wall. Myelography with Amipaque (per Bocquet, Val-de-Grace).

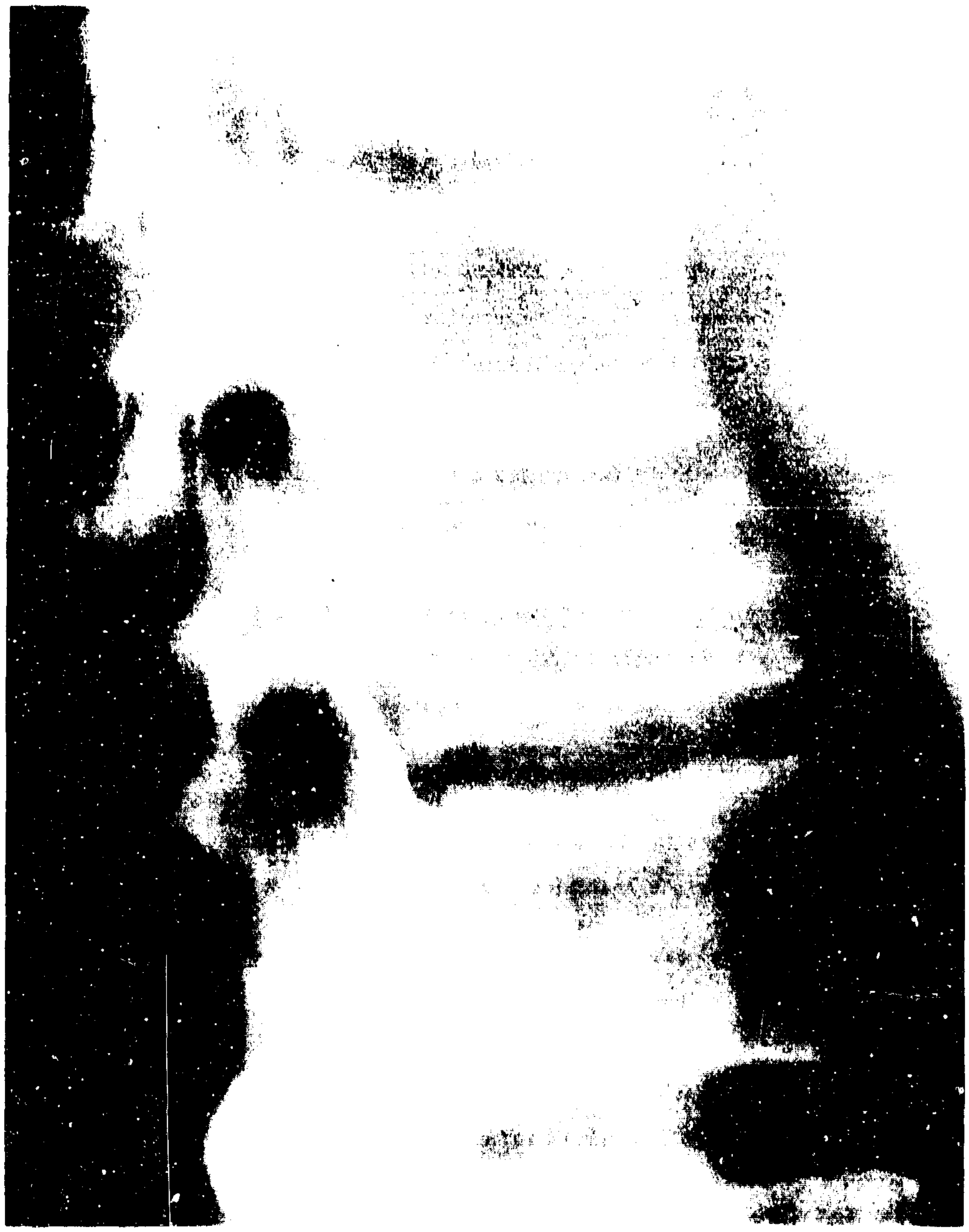


Figure 137. Compression fracture of L1 with paraplegia. Myelography with Amipaque. (per Bocquet, Val-de-Grace).

The role of the radiologist is to assess the instability and the effects of the fracture on the spinal geometry and morphology of the spinal canal.

We have seen that it is necessary to distinguish between:

1. Comminuted Fracture (337, 338)

The stress which produces this is a compressive force acting from front to back. The signs of instability are usually evident in both frontal and lateral views. It should be noted that injury to the surrounding soft tissues is especially important and well seen on scanning (haematoma, rupture of dorsal muscles). Lesions of the disc ligaments are equally prominent.

2. Fracture Dislocation

This follows trauma which acts perpendicularly to the axis of the spine, pushing the upper part of the vertebral column forwards. The fracture line runs obliquely from back to front and from above downwards, passing through the upper third of the vertebral body. The signs of instability are clear. These fractures present two different pictures depending on whether or not the articular processes remain engaged.

Exploration with opaque media (myelography, Figs. 136 & 137) provides fundamental data on the effect of the fracture site of the spinal cord.

3. Fracture of the Laminae of L5 (Figs. 119 & 120)

This is usually the result of a direct impact and is unstable. It is important that the X-ray beam should be perpendicular to the plane of the laminae, and that a tomographic study is made.

5.5.5. Radiological Study of Fractures of the Cervical Spine (C3-C7)

5.5.5.1. Basic Concepts: Recurrent Instability

The cervical column is the most mobile segment of the spine. To this mobility are added the large forces of inertia of the skull (370) during trauma, the small height of vertebrae, and the smaller degree of protection of the spinal cord than exists at lower levels. These different characteristics explain the frequency of severe lesions with neurological complications. In 152 fractures of the cervical spine, Ramadier and Bombart (404) observed 50 medullary lesions and 36 injuries to nerve roots. Witley and Forsyth (450) found 77 neural lesions in 159 fractures of the cervical spine.

Because of their different anatomical, physiological and fracture characteristics, two zones must be considered:

- the cervico-occipital junction - C1/C2

- the subjacent region from C3 to C7.

According to Witley and Forsyth (450), the distribution is 27% for C1/C2 and 73% from C3 to C7. In our own statistical study (see above), we observed 70 fractures between C5 and C7, 15 at C3/C4, and 17 at C1/C2.

Traumatic injuries to the cervical spine are rare in aerospace medicine, but emphasis must be placed on the occurrence in aeromedical practice of these lesions in non-aeronautical activities (road accidents, sport) and on their occupational significance.

The studies devoted to traumatic lesions are very numerous (260, 262, 263, 272, 273, 280, 284, 293, 298, 306, 308, 316, 320, 340, 341, 343, 375, 376, 388, 399, 403, 404, 432).

5.5.5.2. Analytical Study of Traumatic Lesions of C3-C7

SUMMARY

5.5.5.2.1. Review of Important Concepts; Instability is Frequent

Some principles must be stressed:

In a strictly frontal view in a neutral position, the spines are aligned, and the distances between them are more or less equal. Any deviation of the line of the spines is evidence of a unilateral dislocation, and increase in the distance between two spines always indicates a dislocation.

In a straight lateral view, the articular processes are superimposed. If they appear to be separated at a given level when they are superimposed below, a fracture of the articular processes should be sought. The separation indicates a rotation.

Traumatic lesions of the cervical spine are often unstable. Camille's definition of the "middle segment" is particularly applicable to the cervical spine. An injury to one of the constituent components; to the posterior wall and especially to the ligaments, pedicles and articular masses, provides evidence of instability.

This instability is not always evident on standard X-rays. It is sometimes necessary to carry out careful dynamic examinations on a second occasion. These allow the instability to be confirmed if:

- on movement, the angulation of a vertebral body with respect to that immediately beneath it is more than 7-11^{o}

- in flexion, the forward displacement is more than 2-3.5 mm above C4 and more than 2 mm below C4

- more than 50% of the articular facets are exposed.

These abnormal movements signify complete rupture of a ligamentary support.

5.5.5.2.2. Dislocations of the Cervical Spine

These dislocations, usually occurring in hyperflexion accompanied by a rotational movement, are defined anatomically by a loss of contact between the articular processes, the superior processes being displaced forward from the inferior ones (Decoulx (280)).

The sites of predilection are C5/C6 and C6/C7. Sicard (424) and Levarde (360b) distinguish two types; one bilateral and symmetrical, and the other unilateral and unsymmetrical.

Bilateral or Symmetrical Dislocation (Figs. 138 & 139)

This is produced by an injury to the inferior articular processes of the overlying vertebrae, which is displaced in front of the superior articular processes of the vertebra below. It produces an irreducible lock. Different authors appear not to agree in their estimates of the frequency of an associated fracture of the articular processes. Whatever this may be, it consitutes an

Figure 138. Fracture-dislocation of C5-C6 (parachuting).

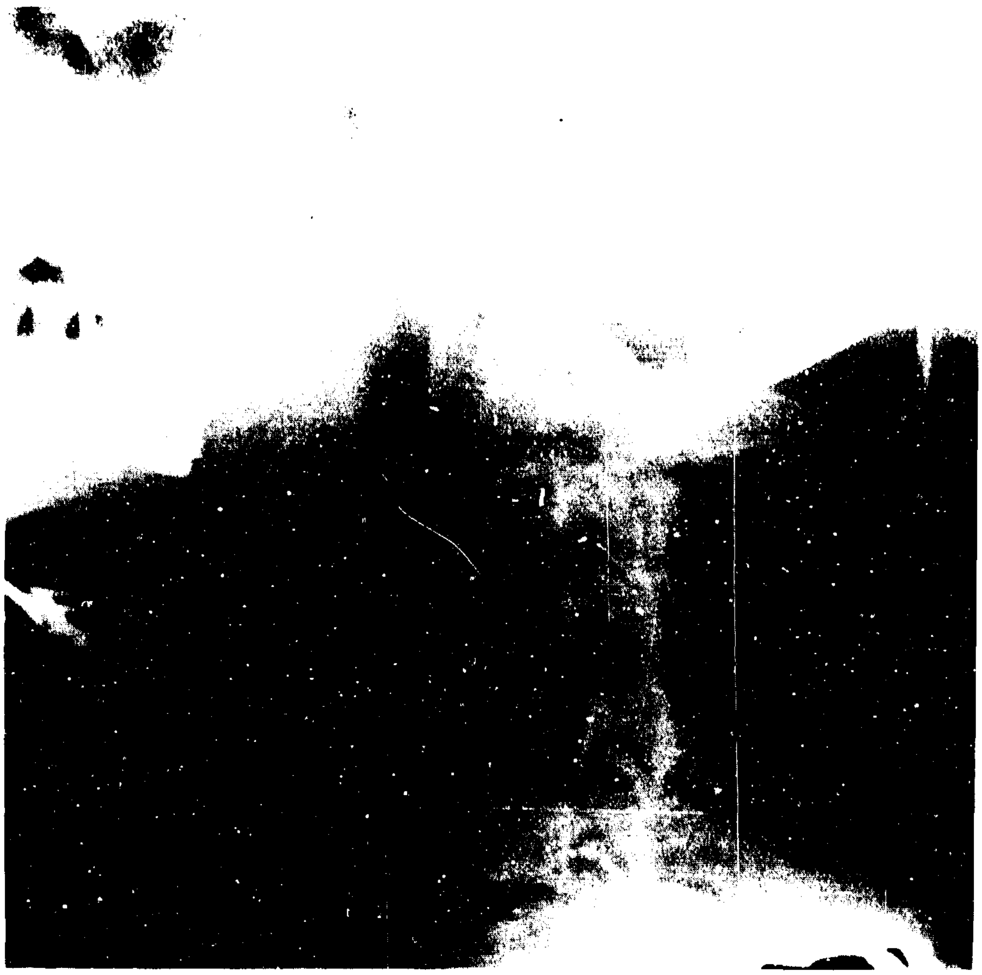


Figure 139. Fracture-dislocation of C4-C5 (parachuting).

extremely severe lesion leading to narrowing of the spinal canal and often of compression of the spinal cord.

The displacement can be seen only in the lateral view. It is very desirable to use a telescopic stand or arch to allow lateral X-rays to be obtained in the prone position, without moving the casualty. The frontal view may be normal.

A particular type, the transitory subluxation described by Watson-Jones (448) may be revealed in dynamic exposures.

Unilateral or Asymmetrical Dislocation (415)

This is due either to the fracture of a single articular process, or to dislocation (with locking). The radiological diagnosis of this form is more difficult, because of vertebral rotation in the horizontal plane, which can narrow an intervertebral foramen. In frontal views, displacement of the spinous processes should be sought, but it is often an unreliable sign. In fact, more than 40% of young subjects exhibit a scoliotic posture of the cervical column. Lateral, and particularly oblique views which can confirm the constriction of the foramen, should be supplemented by tomograms taken at an oblique angle (laminae, intervertebral foramina, articular processes).

5.5.5.2.3. Sprains and Minor Trauma

De Rackers and Ectors (402) have demonstrated the value of a radiodynamic study in the evaluation of sprains and minor trauma of the cervical spine. Louis (367) has recently stressed the importance of diagnosis of severe sprains and lists his criteria:

- the static and dynamic misalignments of the body that we have already described

- functional blocks (284, 285, 115, 394). Two or more vertebrae remain locked together in all positions of the spine. The terms rigidity or reversal of curvature are often used to describe the condition, but the expression "functional block" better indicates the persistence of a postural anomaly in flexion or extension, or in both. There is often a double lock above and below the interface, which facilitates the hypermobility (sic). When the functional block is single, the hypermobility is immediately above it.

In the absence of anatomical evidence it is only possible to speculate on the origin of these lesions:

- deterioration of a disc

- block by jamming of an interapophyseal meniscus

- elongation or tearing of articular ligaments and capsules leading to muscular spasm.

5.5.5.2.4. Fractures

These lesions are less common in isolation than dislocations and fracture dislocations. They consist of:

1. Anterior wedge compression fracture of C5, C6 or C7, and more rarely of C3 or C4. It is centred on the upper vertebral surface, but in some cases the damage simultaneously involves both the upper and lower surfaces. This type of isolated fracture is, as a rule, stable (Fig. 142).

2. The so-called "teardrop fracture" is unstable. It comprises (Fig. 143):

- anterior compression of the vertebral body by hyperflexion

- the detachment of an anteroinferior fragment of the body by hyperextension

- backward movement of the posterior wall into the spinal canal - the vertebra is slightly rotated backwards about its transverse axis

- widening of the posterior articulations and of the space between the spines.

The teardrop is an unstable fracture which may be associated with an anterior spinal cord syndrome characterised by complete motor paralysis and the loss of sensation for pain and for temperature.

Figure 140. Cervical sprain (crash) - functional lock in flexion.

Figure 141. Cervical sprain (crash) - straight in neutral position.

Figure 142. Crush fracture of C7. Epiphyseal nucleus not joined to spinous process of C7 (parachuting).

Figure 143. Tear-drop fracture of C5 (parachuting - impact in the air).

Figure 144. Fracture-dislocation of C5-C6 (Light aircraft crash).

Figure 145. Fracture of spinous processes of C3 - C6.

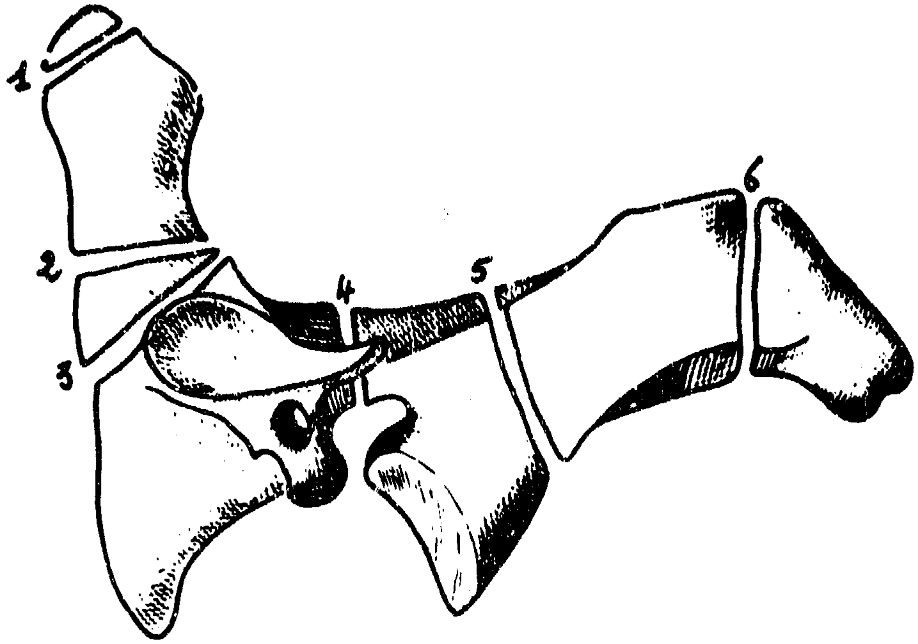


Figure 146. Fractures of the axis (from Sicard)

1) Tip of odontoid
2) Neck
3) Base of odontoid
4) Pedicle of C2
5) Posterior arch
6) Spinous process

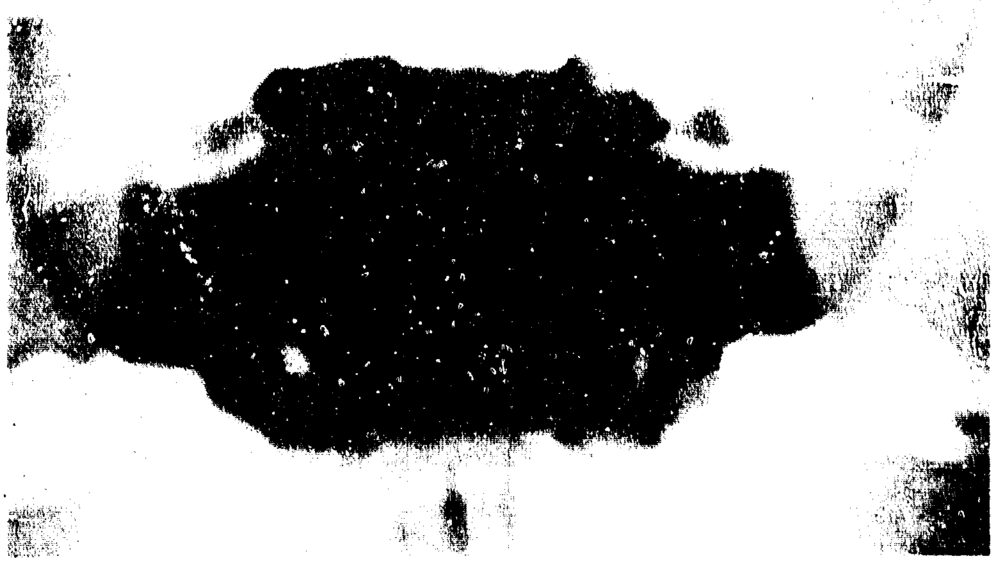


Figure 147. Fracture of odontoid process.
Fall onto the head on landing - Standard radiogram.

3. "Bursting" Fracture

This fracture, which results from axial compression, is seen from C5-C7. There is impaction of the nucleus pulposus into the vertebral body, leading to a vertical fracture line or a comminuted fracture. From the front, the distance between the pedicles is increased. Backward displacement of the posterior fragment is sometimes responsible for nerve lesions. It is, however, a stable fracture because the anterior longitudinal ligament and the interspinous ligaments are intact, but the wall of resistance is disrupted (340).

4. Comminuted fractures appear on radiograms as the breaking up of the vertebral body into many fragments of different size, and there is invariably injury to the posterior arch (unstable fractures (340, 341, 431)).

5. Fracture dislocations (Fig. 144) are the most common traumatic lesions to the lower five cervical vertebrae. These are unstable fractures which, on lateral radiograms, show a greater or lesser degree of displacement of the anterior line, and fragmentation of the vertebral body. From the front, a pronounced "bayonet" displacement and an increase in the distance between the spines are seen. In oblique views and tomograms, some degree of narrowing of the intervertebral foramen is apparent. The greater the encroachment upon the canal, the less chance there is that it is a compression fracture, and the greater the risk of transection of the cord (360b). However, displacements can be very large without causing neurological lesions (399).

6. Special Sites (Fig. 145)

a. The trauma sometimes selectively involves the spinous processes of the lower five cervical vertebrae. The most frequently damaged is C7, and the line of the fracture lies at the base of the spinous process, which is often detached from the vertebral mass. This traumatic injury must not be confused with an anomaly of ossification of the spinous process (persistence of the cartilaginous bridge). In this latter case, the clear line which separates the end of the spinous process is broad. The other vertebrae sometimes show multiple fractures of the spinous processes and upward displacement is not uncommon (Fig. 145).

b. Fractures of the transverse processes are very rare. That of C7 is longer and more vulnerable than the others, and it may be avulsed (257).

c. Fracture separation of the articular mass takes two forms; one at the level of the pedicle, the other posterior, on the lamina. The free articular mass sometimes swings forward. On the frontal view, there is a vertical oblique fracture line on a lamina, and a corresponding asymmetry of the articular mass. On the lateral oblique view of the fractured lamina the line is visible on the pedicle. In lateral views, one of the articular masses is displaced relative to the other. This is an unstable fracture accompanied, in more than half the cases, by a neurological syndrome.

A particular problem is posed by the picture of a post-traumatic quadriplegia without radiologically detectable bone injury (327). This may be due to a sprain, to a dislocation that has spontaneously reduced, to a disc herniation, or to a vascular lesion. More complex investigations - myelography, scanning, discography, arteriography - are then indicated.

5.5.6. Radiological Study of Fractures of C1 and C2

SUMMARY

These represent 15 to 25% of fractures of the cervical spine, and preferentially affect the odontoid. The angles from which the X-rays are taken must be strictly controlled. The frontal view can only be interpreted if the spinous process of C2 is projected on the centre of the body of the atlas. In profile, in the normal state, the posterior border of the odontoid should lie on a straight line extended from that of the body. In contrast, the anterior border lies obliquely. The space between the anterior edge of the odontoid and the posterior border of the anterior arch of the atlas should not exceed 3 mm. The state of the soft tissues in front of the spine should always be carefully assessed. During inspiration, their thickness should be less than 3 mm at the level of C3.

5.5.6.1. Fractures of the Axis (Fig. 146)

These result from trauma to the head or the face, involving hyperflexion and pushing forward of the cervical spine (fall from a height, fall of a heavy load upon the head, traffic accidents). The fracture may involve:

- the odontoid process (tip, neck, base)

- the body of the axis

- the posterior arch.

1. Fracture of the Odontoid (Figs. 147-150)

Fracture of the odontoid process is the most common, the most dangerous, and the least often recognised. If neglected, it does not unite, and there is a persistent risk of neurological lesions (256, 266, 280, 322, 360, 403, 405, 434, 448).

Frontal radiograms taken with the mouth open show the presence of a horizontal or oblique fracture line involving the base of the odontoid process. This line usually has sharp, irregular, crenellated edges, which are easily seen in tomograms. Observation of the base of the odontoid by the lower edges of the two arches of the atlas can lead to confusion; hence the importance of tomography. Dislocation or subluxation of the atlas which is no longer restrained by the odontoid is accompanied by a rotation which changes the relationships of the atlanto-axial articulation; an important indirect sign.

A lateral radiogram properly centred on C1/C2 defines the displacements that accompany fracture of the odontoid process which remains attached to the anterior arch. The fracture line is less well seen in the lateral, but is easily traced in the tomograms. It is necessary to look for displacements, because allied conditions (dislocations and subluxations) are very common. The concave line formed posteriorly by the insertions of the laminae into the bases of the spines, which defines the posterior limit of the spinal canal, must be followed. If the alignment has been lost, the vertebra opposite the displacement has slipped.

Dislocation of the atlas is the commonest and most dangerous complication of fractures of the odontoid. The stability of the atlas depends on the transverse ligament, which surrounds the odontoid from the anterior arch of the atlas. If this ligament is lacerated or ruptured, the atlas may then be displaced forwards.

Figure 148. Fracture of odontoid process.
Fall onto the head on landing - Tomogram.

Figure 149. Fracture of odontoid process (Light aircraft crash).

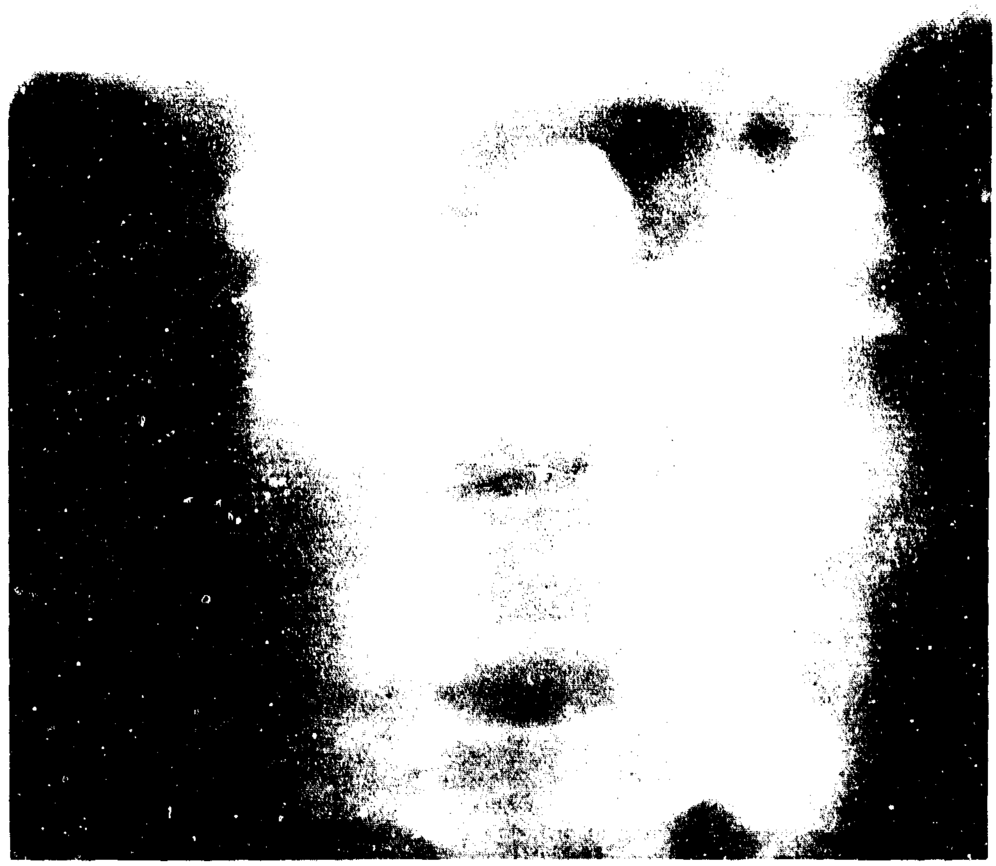


Figure 150. Fracture of odontoid process.

Figure 151. Pseudarthritis of odontoid process.

Figure 152. Fracture of posterior arch of C2 (parachuting).

Figure 153. Fracture of posterior arch of C2 (crash).

Most frequently, the dislocation of the atlas is forwards. In front, it leads to an atlanto-occipital block, and threatens the casualty with serious neurological complications. There is a risk that the spinal cord will be pinched between the posterior arch of the atlas and the body of the axis by a mechanism similar to that of a cigar cutter.

Lateral negatives and tomograms show:

- tilting of the odontoid with respect to the body of the axis

- forward displacement, with the posterior border of the odontoid process aligned vertically to the anterior face of the atlas

- forward tilting of the atlas

- disjunction of the spines, which are separated, breaking the arch formed by the junction of the laminae

- loss of the normal parallelism between the posterior arch of the atlas and that of the axis. The two arches diverge and are open at the back.

Less often, the atlas is dislocated backwards. The odontoid follows the atlas as it tilts, and the processes of the atlas and of the axis may come into contact. Their posterior arches approach each other. In this case, the odontoid directly threatens the anterior surface of the spinal cord, which explains the high incidence of immediate neurological complications.

Evolution: fracture of the odontoid process evolves spontaneously towards a pseudarthritis, with vascularisation coming primarily from the body of the axis (Fig. 151).

The risk of secondary displacement dominates the entire history of fracture of the odontoid and its neurological consequences. With surgical treatment (reduction and immobilisation) consolidation, or at least the development of a reasonably firm fibrous callous, can be anticipated. Radiology allows consolidation, and especially stability, to be confirmed and assessed. Post-operative monitoring should include lateral views in flexion and in extension.

Other fractures of the odontoid process are more uncommon. Fracture of the tip is very rare. An oblique fracture line below and in front isolates a round or oval bony fragment. It is important to distinguish this from a congenital abnormality. A sharp discontinuity and irregular crenellated contours are points suggestive of a traumatic origin.

Fracture of the base of the odontoid, which is the type usually described (see below) sometimes produces an oblique fracture line running from above downwards and from back to front, and reaching the anterosuperior corner of the body of the axis. In this type, the fracture is partly in spongy tissue, and it usually consolidates well.

2. Fracture of the Body of the Axis (293, 360, 424, 448)

The oblique or vertical fracture line passes behind the base of the odontoid process. It divides the anterior third or half of the body of the axis in the anteroposterior direction. This line, which is sometimes visible in frontal views, can only be completely assessed from tomograms. There is no displacement and usually no problem with consolidation.

3. Fracture of the Posterior Arch of the Axis (259, 293, 424, 426)

De Mourgues and Fischer (455) have recently stressed the frequency of this lesion, which is still called "hangman's fracture" in the English literature. Hanging produces an abrupt hyperextension of the cervical column and leads to fracture of the posterior arch of the axis with forward dislocation of the body of C2 on C3. This particular lesion can occur during automobile accidents or in accidents at work (falls from scaffolding). The incidence is certainly greater than would appear from the study of different surgical statistics. After all, de Mourgues and Fischer have treated 30 recent cases!

Tomograms define the topography of the fracture line, which involves the posterior arch of the axis, and also possible displacements: sliding of the body of the axis in front of the third cervical vertebra.

These fractures of the posterior arch of the axis (hangman's fracture) tend to consolidate spontaneously if reduction is good and proper restraint is ensured (Figs. 152 & 153).

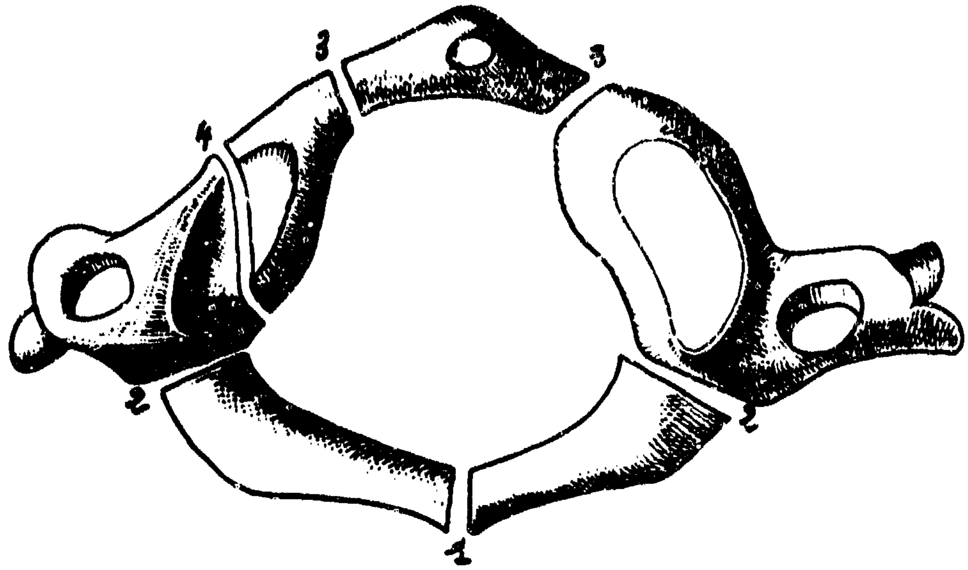


Figure 154. Fractures of the atlas (from Sicard).

1) Median fracture of posterior arch
2) Fracture of posterior arch
3) Fracture of anterior arch
4) Fracture of lateral masses

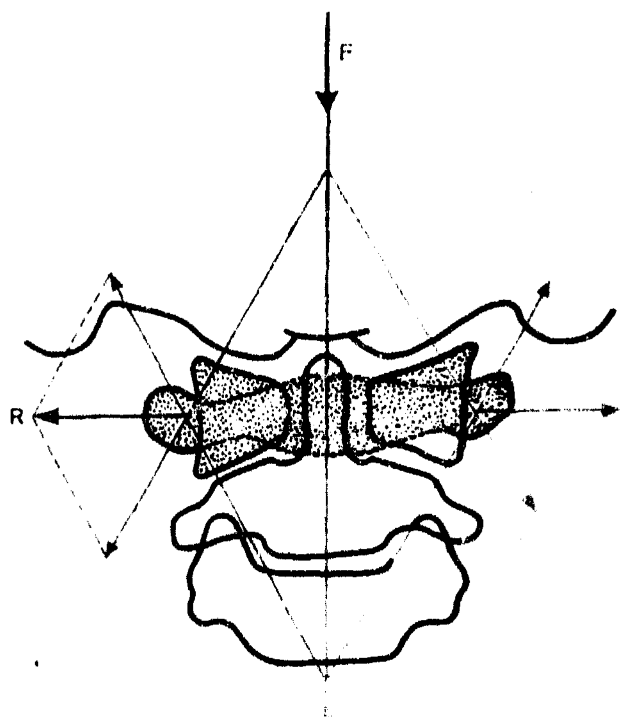


Figure 155. Diagram from Jefferson.

The traumatic force (F) transmitted to the atlas through the occipital condyles (in a fall onto the head) is opposed by a force (F) in the opposite sense. The resultant of these forces (R) derived by the parallelogram rule is essentially horizontal, and tends to push the lateral masses outwards.

Note that the wedged shape of the lower external face and upper internal face of the lateral masses potentiates this displacement from the centre.

5.5.6.2. Isolated Fractures of the Atlas (Fig. 154)

These are often missed, because they are difficult to detect on radiograms. Almost without exception, these fractures result from indirect but always violent trauma, causing hyperextension of the head. The force diagram devised by Jefferson explains the development of fracture separation where a high loading in the vertical sense, caused by a violent impact of the head, is associated with hyperextension. The scanner plays an important role in the diagnosis and localisation of such fractures (347). Standard radiograms and tomograms allow three types to be defined (293, 423):

- fracture of the lateral masses

- isolated fracture of the posterior arch

- fracture of the anterior arch.

1. Fracture of the Lateral Masses - Jefferson's Fracture (433) (Fig. 155)

Most frequently bilateral, these are due to overload (see figure from Jefferson). This produces a fracture of the lateral masses, which separate from one another and slide outwards if the transverse ligament is torn or if one of the tubercles is detached. On tomograms, deviation of the lateral masses should be looked for, associated with a greater or lesser loss of contact at the atlanto-axial interface. Less frequently, a bony fragment is detached from the internal face of one of the lateral masses by contraction of the transverse ligament. This type of fracture does not entail neurological complications, because it widens the spinal canal rather than narrowing it. It frequently leads to painful sequelae associated with neuralgia in Arnold's nerve (the auricular branch of the vagus) or with atlanto-axial arthritis.

2. Isolated Fracture of the Posterior Arch of the Atlas

During a movement in hyperextension, the posterior arch of the atlas, which is squeezed between two stronger bony surfaces (the base of the occiput above and the posterior arch of the axis below) gives way at its weakest point. The line of fracture rarely lies in the mid-line (distinguishing it from a congenital spinal fissure). Located almost always in the lateral parts, and sometimes on both sides, it involves the region behind the lateral masses. Tomography usually confirms the presence of two lines which are frequently symmetrical. There is no displacement because the powerful vertical muscular and ligamentous braces hold the fracture in place. Moreover, there are no forces which naturally tend to push the fragment forward or backward.

3. Fracture of the Anterior Arch of the Atlas

Less common than fracture of the posterior arch, this is most frequently associated with other lesions of the atlas and especially with other cervical fractures. The displacement is small, and tends to be in the forward direction as a result of pressure from the odontoid process.

5.5.6.3. Dislocations

Very rarely occurring in isolation, these are usually associated with fractures. They comprise:

- atlanto-occipital dislocation; this is exceptional and leads to immediate death by damage to the medulla oblongata (cigar cutter mechanism) (293, 424, 448)

- dislocation at C2-C3; this results from a fracture of the posterior arch of C2 at the level of the pedicles. The axis slides forward on C3, carrying with it the atlas and the occiput

- atlanto-axial dislocation; almost always associated with a fracture of the odontoid process, this occurs in three directions; anterior (the most frequent), posterior, and lateral (293, 314).

The lateral view defines the degree of slippage. Atlanto-axial dislocation sometimes occurs without fracture of the odontoid by traumatic rupture or disinsertion of the transverse ligament.

From the strictly lateral aspect, the separation between the anterior arch of the atlas and of the axis can be determined. It varies from 2 mm in the adult to 5 mm in the child.

It should be noted that this dislocation sometimes occurs spontaneously or as the result of trauma in some infectious processes (Grisel's torticollis, high foci of rheumatoid arthritis, ankylosing spondylitis).

Figure 156. Functional lock of occiput & atlas with sub-jacent hypermobility (from Wackenheim).

a) extension
b) neutral
c) flexion

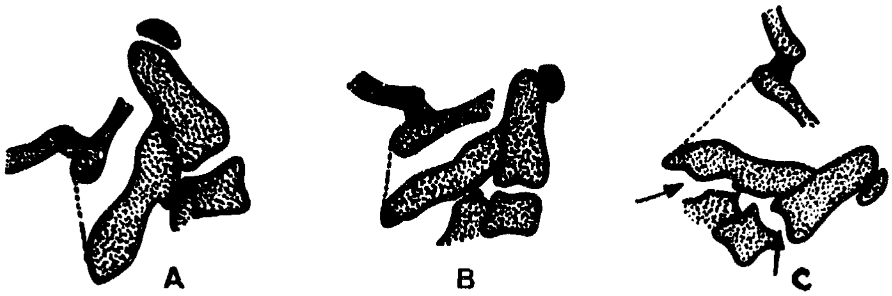


Figure 157. Functional lock of C1-C2 with sub-jacent hypermobility (from Wackenheim).

a) extension
b) neutral
c) flexion

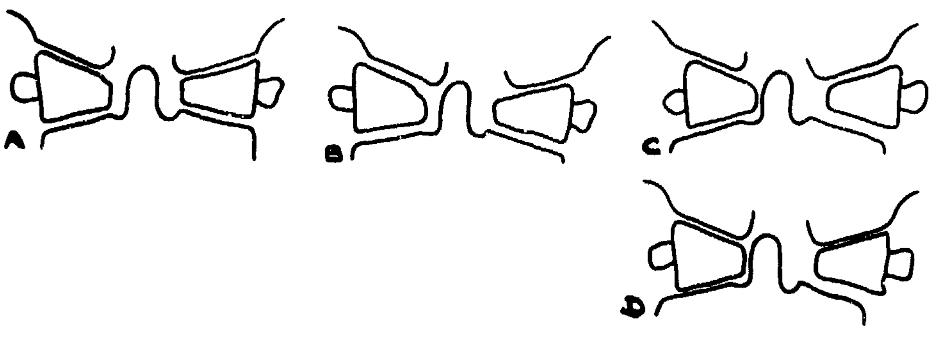


Figure 158. Sideways dislocation of the occipito-cervical junction (from Wackenheim).

a) normal appearance
b) condylar dislocation
c) atlantoid dislocation
d) condylo-atlantoid dislocation

5.5.6.4. Traumatic Subluxations (Figs. 156, 157 & 158)

Studied particularly by Wackenheim, these involve disturbances in the relationship between the occiput, atlas and axis with respect to the midline represented for the cranial slope by the intervestibular line and the bisector of the condyle angle. As this author stresses, high-quality tomograms passing through both labyrinths must be obtained, and good position of the shoulders must be ensured. Actually, because of the obliqueness of the articular surfaces, simple rotation can produce pictures resembling those of pathological changes:

- slight separation of the articular surfaces by rotation of the axis on the atlas

- the odontoid process not in contact with the anterior arch of the atlas (lateral view).

Radiodynamic studies in lateral flexion are of great importance in the diagnosis of these conditions, which must be distinguished from asymmetry of congenital origin.

5.5.6.5. Sprains and Minor Trauma

By means of dynamic radiography, static and dynamic misalignments and functional locks can be found at the level of C1 and C2. Two or more vertebrae behave as a single unit in all positions of the spine. The following types can be distinguished:

- atlanto-occipital lock, which may be due to tearing of the posterior atlanto-axial ligament

- atlanto-axial lock probably related to rupture of the posterior atlanto-occipital ligament.

These locks lead to a compensatory hypermobility in C2/C3, immediately below them.

5.6. SEQUELAE OF VERTEBRAL FRACTURES AND TRAUMA

R P. Delahaye and P.J. Metges

SUMMARY

5.6.1. Principles of Treatment

After an accident or an ejection, pilots and parachutists are usually examined by a specialist in aviation medicine and often sent to a hospital centre. There, the casualties are examined clinically and radiologically and then treated, in case of need, in an orthopaedic surgery department. Often, the initial evaluations are made by a flight surgeon who, in many air forces, armies (parachuting, light aviation), or navies (carrier aircraft), serve on the Boards of Enquiry. These clinical data, obtained on the spot, are frequently very important.

The broad principles of treatment of traumatic lesions and fractures of the spine in aviation medicine are no different from those followed in general practice: for example, in accidents at work, on the road, or in sport. We present a general scheme in accordance with the different philosophies of various schools of orthopaedic surgery, and contrast the very common thoraco-lumbar fractures of the spine with the more severe fractures of the cervical spine.

5.6.1.1. Fractures of the Thoraco-lumbar Spine

Simple compression fracture:

- strict bed rest on a hard surface - immediately;

- early rehabilitation provided that the fracture is stable and uncomplicated; pain does not appear to be a contraindication to rehabilitation;

- out of bed after 3 weeks.

Fracture with enucleation:

- rest in bed for 4-6 weeks

- rehabilitation starting later, (on average, from the third to the fourth week) because this type of fracture is more painful.

Complex fracture:

- neurological complications, if they do not regress in the first hour, are often permanent; nevertheless, surgical treatment is necessary to stabilise the fracture and to allow easier nursing

- when there are no neurological complications, stabilisation of the fracture site by orthopaedic or surgical techniques (bone grafting in particular) is carried out; the technique used depends on the type of the lesions.

Multiple fractures:

- by severe compression, particularly in the thoracic spine, these can profoundly modify the spinal geometry and after rest of variable duration (3-6 weeks) on a hard surface, demand prolonged rehabilitation.

5.6.1.2. Fractures of the Cervical Spine

The whole prognosis depends on the presence or absence of neurological injury, and equally on the value and reliability of the early radiological examination. For the most part, the fractures are unstable, and surgical treatment is required either by orthopaedic reduction and a Minerva plaster with extension and in traction, or by bone grafting.

5.6.1.3. The Duration of Incapacitation

Because of the extreme variation in the different types of spinal fracture encountered in aviation, it is difficult to determine this with certainty. From the outset, unstable fractures, which are fortunately rarer, usually lead to a very long period of incapacitation; unfortunately, they nearly always lead to a ruling of permanent unfitness for all flying duties.

5.6.2. Clinical Study of the Sequelae of Spinal Trauma

We can distinguish three categories of casualties:

- those in whom the fracture has been overlooked

- those in whom the lesion was recognised and treated, and who present with a syndrome of delayed pain

- those in whom the immediate clinical and radiological findings were negative, but who later complain of pain.

5.6.2.1. Cases With Undetected Fracture

Most often, the fracture is missed for want of a radiological examination; a fact which justifies the systematic radiography of the entire spinal column of pilots and parachutists involved in accidents.

In many air forces, such radiological examinations are mandatory. Knowing the silent clinical picture presented by some vertebral compressions and the fundamental importance of comparing the results of examinations made on recruitment of flying personnel with those after an accident, we cannot but congratulate ourselves on the application of a rule that has proved so beneficial for the casualty and for the air force.

As a corollary, an impeccable radiological technique must be employed with very frequent recourse to tomography.

Clinical Aspects

Secondary pain appears, which is usually localised in a well defined region, and is exacerbated by the upright posture, by fatigue, or by physical exertion in a stooping posture. This pain sometimes has a paroxysmal character with nerve root irradiation (9, 354, 356).

The paravertebral muscle masses are atrophied and hypotonic. The mobility of the spinal segment is reduced. The spinous processes are sometimes slightly painful to palpation.

Standard radiograms and tomograms reveal signs of fracture: anterior wedge compression or damage to the transverse processes.

5.6.2.2. Cases Recognised and Treated, and Presenting with a Syndrome of Delayed Pain (354, 356)

The pilot or the parachutist consults the doctor for back pains which follow the accident after a delay varying from a few weeks to several years. The source of these painful phenomena should be sought in persistent muscular or ligamentary insufficiency resulting from incomplete functional rehabilitation of the patient, who has not always understood the need for this treatment. Many aircrew and parachutists think only of resuming their flying activity, and despite all advice and all warnings, they remain unreceptive. Moreover, others return to flying duties apparently cured and no longer suffering, only to become victims of more or less severe trauma (road accidents, difficult parachute landings on rough ground) or they may suffer a return of pain after an aerobatic session in a fighter aircraft or a fairly long flight in a helicopter.

5.6.2.3. Cases with an Initially Negative Clinical and Radiological Picture, but with Pain

The most thorough radiological examination, including radiodynamic studies and tomograms, may reveal virtually no lesions in a pilot or a parachutist who suffered trauma to the cervical spine several weeks or several months earlier.

The patient complains of diverse symptoms, which form a fairly characteristic clinical picture called the "cervical trauma syndrome", which comprises (296, 303, 419, 444):

- headaches

- cervical pain

- auditory and vestibular disturbances

- visual symptoms

- psychological disorders.

1. Headaches are the most common. They consist of paroxysmal pains, usually unilateral, located in the occipital region and radiating towards the parietofrontal region, and sometimes brought on by a mechanical stimulus. They may be accompanied by disorders of sensation (hypo- or hyper-aesthesia (296)).

2. Cervical pains, which tend to occur at night, are often unilateral and form the site of onset of migraine, are sometimes triggered by movement or by holding the cervical spine in one position.

These cervical pains sometimes radiate towards the upper limbs, but the irradiation rarely has the characteristic distribution of any of the cervical nerve roots. Sometimes, but less commonly, cervico-brachial or cervico-occipital neuralgia develops. The latter, which is unilateral and has temporal and suborbital irradiation, is accompanied by lachrymation and by paresthesia of the scalp.

3. Auditory and vestibular disturbances comprise various acoustic phenomena:

- humming, hissing, and "rain-fall" noises, a feeling that the ear is blocked. Often unilateral, these symptoms are rarely associated with objective signs on audiometric examination

- the disorders of vestibular origin are forms of vertigo:

  . true rotational vertigo,

  . simple feelings of transient instability and insecurity, often brought about by a particular position of the head.

We have twice encountered spontaneous nystagmus (once in a professional parachutist and once in an air hostess).

4. Psychological disturbances, even in the field of aviation, takes the form of symptoms of anxiety or depression, or of disturbances of sleep, of sustained attention, or of long term memory (303, 444).

Clinical examination usually reveals a painful limitation of movement, which is rarely specific, but is brought on primarily by rotation. The pain of extreme movements is almost constant, and two regions are particularly affected: the cervico-thoracic junction and the cervico-occipital region.

Pathogenesis

This syndrome may be similar to that described by Barre and Lieou. It would then be due to a vasoconstriction in the vertebral arterial system, through compression of the posterior cervical sympathetic nerve (296, 303, 419).

5.6.3. Anatomico-pathological Changes at the Fracture Site (293, 358, 448)

Anatomical and pathological studies provide an understanding of the mechanisms in the different radiological appearances of the fracture site, and their development. The contrast between stable and unstable forms shows the value of this classification.

Figure 159. Crash - Fractures of L1, L2, L3, L4 - Appearance 1 month after the accident.

Figure 160. Subsequent appearance of fractures of D6 & D7 (ejections).

Figure 161. Helicopter accident 2 years previously; sequelae of fractures of L3 & L5.

Figure 162. Sequelae of fracture of L2, seen as wedge compression of L2 with breakage of the upper vertebral plateau and of the lateral border (crash).

Figure 163. Parachuting accident. Sequelae of fracture of L1 with wedge compression and narrowing of D12/L1.

Figure 164. Sequelae of sagittal fracture of L3 (Helicopter accident 2 years previously).

Figure 165. Sequelae of crasn 5 years previously, showing calcification of ligaments.

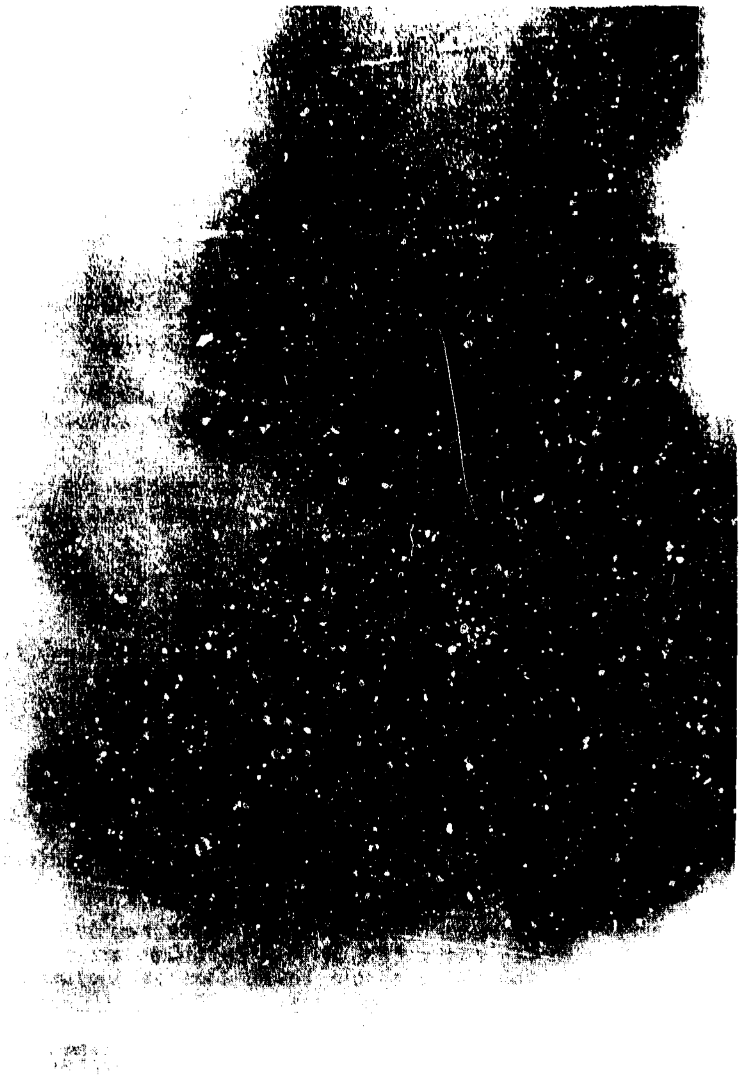


Figure 166. Sequelae of comminuted fracture of D6 (4 years after an ejection).

5.6.3.1. Early Development

In stable forms, the compression of the vertebral body reaches is maximal from the outset and there is no risk of further deterioration. Early mobilisation is possible.

In unstable forms, secondary displacement, which is potentiated by the degree and severity of the lesions to the bones, ligaments and discs, can result from the smallest movement of the patient (transport, radiological examinations or even simply in bed). Immobilisation must be strictly maintained until fixation of the lesion begins. A bony or fibrous callous or simple fibrosis of the soft tissues appears after a delay of 1 to 3 months.

5.6.3.2. Late Development (253, 448)

1. The Bony Site

The healing of vertebral fractures takes place in two stages:

- formation of a callous in the disrupted spongy tissue

- healing by periosteal callous; this process, which is less marked than in fractures of the long bones, does not appear to be accepted by all authors.

On radiograms, the consolidation is marked by the appearance of small calcified fragments, separate from the anterior ligament, and by the formation of marginal osteophytes.

What must be said of the Kummell-Verneuil syndrome in 1980 (279, 297, 357, 372)?

Before the discovery of X-rays, Kummell (1891) and Verneuil (1892) described a syndrome characterised by three stages of development:

- initial trauma with slight, transitory clinical signs

- a silent interval

- secondary appearance of kyphosis with a return of pain.

Kummell and Verneuil attributed this clinical picture to secondary vertebral compression caused by post-traumatic osteoporosis.

Such secondary collapse of the vertebral body has been reported many times. In the absence of radiological examination carried out immediately after the trauma (24-72 hours) it is not possible to hold a single observation as indisputable evidence of progressive secondary collapse.

Mangin, Delahaye and Buchet (372) carried out a retrospective survey of 102 cases of spinal trauma occurring in aircraft accidents (1951-1961 inclusive). They compared the results of radiograms made in the 24 hours following the accident and those made later, in 1962-63. There were 16 compression fractures and 86 cases of trauma without initially detectable lesions. No late vertebral compression was revealed by various radiological procedures. The techniques used (standard views and tomograms) were very reliable.

At present, most orthopaedic surgeons, rheumatologists and radiologists concerned with trauma and its sequelae consider that the late, post-traumatic vertebral compression which is the anatomical basis of the Kummell-Verneuil syndrome does not exist.

Radiological examination of the spine should be carried out as soon as possible after any aircraft accident, and the technique should be perfect.

2. The Discs (Fig. 163)

A damaged intervertebral disc almost never regains its original form. By losing its elasticity, it ceases to act as a hydraulic shock absorber for movements of the spine. Post-traumatic calcification of the nucleus pulposus is rare. On the contrary, instead of becoming denser and consolidated, the disc is deformed. It can allow the displacement of one vertebral body on another (for example, functional lock in the spinal column). Exceptionally, the disc degenerates and totally disappears (traumatic lock).

5.6.4. Radiological Appearances of Sequelae (274, 293, 318)

We must again recall that there is no correlation between the severity of the clinical picture and the degree of radiological change.

5.6.4.1. At the Bony Site

Wedge compressions persist. The morphological evolution is variable. Often, there is a localised discrete consolidation at the upper surface of the fractured vertebra, but regularity of the contour is preserved. This is resorbtion. The corner may remain prominent; it continues to "dribble" (Figs. 159 & 160). Rarely, the anterior corner may be reabsorbed, and the vertebral body regains an entirely normal morphology. The intervertebral spaces above and below the fracture often retain their normal height.

In complex fractures, in which there is almost always damage to the posterior wall, the vertebral deformation is very great. The compressed vertebral body is enlarged in the antero-posterior direction (Figs. 161, 162 & 164). The anterior corner re-unites and forms a regular shelf in which it is sometimes possible to observe an imprint caused by debris of the nucleus. The defect becomes blurred, but the appearance of a broken line on the upper vertebral surface persists (Fig. 163). In some cases, the vertebral body is widened, with moderate consolidation in the upper plateau. In severe compressions, a usually incomplete block occurs, in which a more or less complete outline of the intervertebral disc remains. The very early development of marginal osteophytosis indicates the severity of the disc lesion (Fig. 166).

Fractures of the posterior arch consolidate, sometimes with a thick bony callous. In contrast, those of the spinous and transverse processes frequently evolve towards pseudarthritis.

Fractures of the transverse processes heal normally, or progress towards pseudarthritis if the discontinuity is more than a centimetre wide, or if there is already a large displacement.

Absence of consolidation is shown in radiograms by the persistence of one or more fracture lines. It is common at the base of the odontoid process, and also frequent in the spinous and transverse processes.

5.6.4.2. In the Disc and Surrounding Tissues

From the standpoint of anatomical and pathological development, we may distinguish:

- selective nipping or gaping of the disc spaces, which tends to restore the straightness of the spine

- calcification around the disc, in the form of marginal osteophytes or synostosis.

Marginal osteophytosis appears as a dense outgrowth from the edges and corners of the injured vertebra. Often, the underlying vertebra forms a buttress (Figs. 163 & 166).

Synostosis appears in front or at the side of the vertebral body, in the form of a bony bridge which spans the disc and fuses 2-3 vertebrae together. Bony outgrowths from the ligaments are not exceptional. These phenomena are sometimes seen without any change in the height of intervertebral spaces. The role of haemorrhages, particularly into the space around the disc, in the genesis of these synostoses, should be noted (Fig. 165).

Less commonly, the partial (or more rarely complete) disappearance of the disc creates a vertebral lock.

5.6.4.3. Vertebral Displacements

When the surgical treatment has been correct, such displacements are rare. In some cases, especially at cervical level, functional locking or of backward displacement may persist due to neglected fractures of the articular processes.

5.6.5. The Sequelae of Ligamentous Lesions

These usually result from the failure of consolidation of the interspinous ligaments. Delayed pain is a frequent development in the evolution of spinal fractures. Postural disturbances, aggravated by the inadequacy of the muscular splinting, are due more to the persistence of pain than to the development of arthritis.

CHAPTER 6 - POSTURAL DISORDERS IN AVIATION MEDICINE

In this chapter we shall consider, in turn, backache in helicopter pilots and the neck problems caused by flying combat aircraft.

Helicopter flying leads, in some circumstances, to the development of back pain. Its origin and mechanism have been the object of many studies in recent years. It transpires that the posture of the pilot and the presence of vibration both play a very important part in the genesis of the complaint.

Is the cervical spine injured more frequently in the pilots of high-performance aircraft than in the case of other pilots or of a control population not exposed to the same risks?

6.1. BACKACHE IN HELICOPTER PILOTS

R P Delahaye, R Auffret, P J Metges, J L Poirier and B Vettes

SUMMARY

6.1.1. Introduction

It is more than 40 years since the test pilot Maurice Claisse, after an endurance flight in a Breguet-Dorland helicopter, stressed the unpleasant character of the vibrations that shook the entire aircraft:

"Shaken on an uncomfortable platform for an hour of flight, the pilot is in a hurry to land and return to the hangar, to tend to his aches" (40, 75).

In spite of the technological progress made since the flight of the first gyroplane in 1907, this comment reported by Vice-Admiral Jubelin is still largely valid. Reduction in the sources of hazard and annoyance in the cockpit has not kept pace with the technological improvement of helicopters.

Pathological manifestations in helicopter pilots, of which pain is the dominant one, have been extensively studied in France since 1950; the time when these aircraft were first used by the French Air Force. Among the French studies, we shall consider those of Missenard & Ferneau (1957; 171), Fabre & Graber (1959; 88), Montagard, Sais & Guiot (1962; 174, 175), Sliosberg (1962, 1963; 219-222) and Rabischong (188).

Since 1963 the Aerospace Medical Laboratory of the Flight Test Centre at Bretigny (Seris, Auffret, Poirier & Vettes) and the radiology depertments of the Begin Hospital at St Mande and the Dominique Larrey Hospital at Versailles (Delahaye, Mangin, Gueffier, Metges & Colleau) have been concerned in the study of this pathology (40, 52, 61, 75-77, 186, 209, 211, 213).

While vibration has been the subject of very many studies, its clinical aspects have attracted few research workers or clinicians. We may cite von Beckh (20), von Gierke (103, 105), Guignard (118-120), Braunholer (30) and Fischer (95).

6.1.2. Clinical Studies of Backache in Helicopter Pilots

These back pains mainly affect the lumbar region, although they can also occur in the thoracic and cervical regions.

6.1.2.1. Lumbar Pain

Lumbar pain is commonly of two forms; acute and chronic. Very often, these alternate in the same patient.

1. Incidence

Table 6.1 shows the great variation in the incidence of back pain.

TABLE 6.1

YEAR	AUTHORS	NO OF SUBJECTS	INCIDENCE %	
1957	Missenard and Graber (171)	-	50	France (Armed Services)
1962	Montagard, Sais and Guiot (174, 175)	-	60	France (Armed Services)
1963	Sliosberg (200, 221)	128	67	France (Armed Services)
1969	Steyvers (215)	-	80	Belgium
1973	Rabischong-Seris (188)	52	89	France (Armed Services)
1974	Colleau (40)	29	60	France (Navy)
1974	Rance and Chappelow (189)	34	21	Great Britain
1974	Braunholer (30)	-	66	US Navy
1977	Dietrichs cited from von Beck (20)	-	95	FRG
1978	Delahaye and Auffret (75)	12	66	France (Test Pilots)
1978	Schulte-Wintrop, Knoche (205)	145	51	FRG
1979	Fischer and Zittelsberger (95)	221	63	FRG

This incidence varies considerably with the date and the author. The high values seem to us to be very significant. In France, they are related to particular operating conditions of the population under study; pilots in wartime operations (Algeria), test pilots, observers. The great majority of the pilots have more than 1000 hours of flight experience.

In other countries, some authors have also described the occurrence of pain in young pilots. For example, von Gierke et al. (40) reported back pain in 80 per cent of a group of 25 young pilots who were followed from the outset of their flying career.

2. Circumstances of Appearance

All authors agree that there is a delay in the appearance of painful symptoms: it is 300 hours according to Sliosberg (220, 221) and von Gierke (40), and 500-1000 hours according to Montagnard et al (174, 175) and Colleau (40).

In a study carried out at the Bretigny Flight Test Centre (75), this time-lag appears to be even longer (1000-1500 hours). There is considerable individual variation. The delay in the development of pain is reduced by the presence of pre-existing spinal lesions or congenital abnormalities. For example, one pilot with a transitional anomaly of the lumbo-sacral joint complained of pain after only 20 hours of flight.

The frequency of flight plays a supportive role in the symptomatology. Thresholds for the appearance of pain vary, but we may quote the following average values:

- 30 to 40 flying hours per month

- 3 to 4 hours per day

- 1.5 hours per sortie.

3. Symptomatology

Chronic lumbar pain is the most common complaint. The picture is of a low-grade, tiring, heavy ache localised in the lumbar region, or sometimes lower (lumbo-sacral pain). It extends laterally, often predominantly to one side, and may radiate to the buttocks, the iliac crests or, more rarely, the groin. This discomfort is brought on by flight, aggravated by lifting effort or by long car journeys, and relieved by lying down and by physiotherapy.

At a higher level of intensity, this discomfort becomes a pain which makes flying very gruelling so that, despite the constraints upon the position of his limbs, the pilot seeks to change his posture. The pain increases in intensity during the last flight at the end of the day, and reaches a maximum when the pilot lands the aircraft. Although it persists during the evening, it tends to diminish, but re-appears on standing. It disappears after a night's rest.

Examination sometimes reveals a modest degree of painless scoliosis with stiffness and slight paravertebral spasm; more often, the stance is normal and the examination elicits signs only on movement - a small reduction in the Schobert index, or delayed straightening of the lumbar spine.

Eventually, in the final stages, this distressing condition becomes permanent and makes any flexing movement of the trunk very difficult or even impossible during the active phase of flight. On examination, forced hyperextension and forward flexion usually give rise to pain which limits movement of the trunk. There is associated spasm of the paravertebral muscles, with or without lateral deviation of the trunk. The deep muscles of the lumbar region are painful to palpation or pressure. Lasegue's sign can sometimes be elicited, always unilaterally. Palpation also reveals tenderness at the classical Valleix's points, while neurological examination is almost always normal with respect to motor function, sensation and reflexes.

Acute lumbar pains, found in an average of 50 per cent of cases, occur for the most part in an isolated fashion against a background of chronic lumbar backache.

Their mode of appearance is variable; they frequently have a progressive course without a defined initial exertion but after an unusual workload, or they may appear in two stages. The pain does not occur for some hours after flight; sometimes the onset is sudden, but the precipitating effort or awkward movement is then unrelated to aviation (gardening, sport, etc.).

These acute lumbar pains have the classical "girdle" distribution, and consist of very sharp, intense pain which is brought on by the slightest movement; it is located in the lumbo-sacral region, often more on one side than on the other, but usually with radiation to the entire lumbar area and the buttocks, and sometimes even to the thighs.

Examination, which is made difficult by the intensity of the pain, reveals painful spots beside the spine at the level of the lowest discs, paravertebral spasm and, above all, a compensating kyphoscoliosis which remains unchanged during all movements of the spine. Lasegue's sign can be elicited bilaterally.

With rest in the supine position (preferably on a hard surface), and with analgesic, anti-inflammatory and anti-spasmodic drugs, resolution generally occurs satisfactorily in a few days, but the acute pain frequently recurs at variable intervals against a background of chronic pain.

Finally, sciatica (181), which is a major complication of degenerative disc lesions, was found in 2 cases in the series (75), affecting pilots with more than 4000 hours of flight experience who had suffered from lumbar backache for several years. Among 128 subjects engaged in intense work, Sliosberg (220) noted 11 cases.

Clinical examination reveals ipsilateral or contralateral flexion (which helps to relieve the pain), the classical Valleix's points and, particularly, Lasegue's sign. Sciatica affects either the root of L5 or of S1, often with abolition of the Achilles tendon reflex. In general, no signs of major neurological deficit are noted; in one of the two cases from the study (75) they were, however, present in the form of paralysis of the L5 type, due to a very large herniation of the intervertebral disc which required surgical intervention.

6.1.2.2. Thoracic Pain

This is usually more an aching or soreness than a true pain, centred in the middle part of the back (D6-D7), and eased by extension of the trunk. It is often associated with lumbar pain. Sliosberg (220, 221) and Colleau (40) found an incidence of about 40 per cent. For our part, we have not encountered any truly thoracic pain; this difference is explained partly by improvement in the pilot's position and the comfort of the seat back, but mainly by the fact that Colleau was dealing with Naval pilots who carried on their backs a folded dinghy and its inflation equipment, with a total weight of 8 kgs. This assembly forms an uncomfortable back-pack which is ill-adapted to in-service seats, and the constraints are still more accentuated by wearing a Mae West (40).

6.1.2.3. Cervical Pain

In his study (220), Sliosberg noted that 30 per cent of patients presented with low or middle cervical pain, which sometimes radiated to the shoulder or upper arm in the form of brachial neuralgia. The pain sometimes appeared in isolation, but was more often associated with lumbar pain. Colleau (40) found only two cases (out of 29), and he attributed this reduction to improvement in the visibility at the controls of a modern aircraft.

Other pilots merely report aching at the nape of the neck, brought on by extreme movements of the head and usually made worse by wearing a protective helmet.

6.1.3. Radiological Studies of Backache in Helicopter Pilots

6.1.3.1. Lumbar Spine

1. Montagard et al (175) published the first radiological study, involving 60 pilots (37 instructors and 23 students). They emphasised the frequency of scoliosis without imbalance of the pelvis (34 of 60 cases, or 56 per cent). Some were mild, with minimal rotation of the spine, but others were more pronounced, with significant rotation.

In addition, Montagard et al found four anomalies of the lumbo-sacral joint; two of them being sequelae of Scheuerman's disease (osteochondrosis). The clinical and radiological correlation was interesting; of the 34 scoliotics, 13 complained of back pain.

2. The studies carried out at the Dominique Larrey Hospital by Delahaye, Seris and Auffret, reported in references 52, 211 and 213 and in the thesis by Colleau (40) were different. They concerned 70 helicopter pilots and engineers presenting with painful backs.

In 30 per cent (20 cases), the radiographic appearances were normal. In contrast, in 60 per cent (42 cases) there was a scoliotic posture without rotation of the vertebrae, generally centred at L1 or L2 and without any great change in the spinal morphology. Dynamic studies (radiograms taken in lateral flexion) did not reveal selective widening or narrowing of the disc spaces.

In 10 per cent of cases (7 pilots), there were signs of arthritis at L4-L5 (osteophytosis of the anterior margin in 5 cases, posterior and inferior osteophytosis of L5) and the sequelae of trauma (anterior wedge fracture of L2 in one case).

3. From these two studies, it is possible to draw some conclusions: the incidence of scoliosis (i.e. of curvature of the spinal axis without rotation of the vertebral bodies), or of slight scoliosis in which the deviation is accompanied by some rotation of the vertebral bodies, is 70 per cent among the so-called normal population (see Chapter 7) (56, 58, 289, 290, 291).

It seems that this solitary change of posture in the frontal plane cannot be regarded as evidence of a pathological process, unless it involves a compensatory (pain-relieving) curvature with paravertebral spasm.

It is difficult to be sure of the specificity of some anatomical changes in the vertebrae, especially arthritis. Nevertheless, the signs of arthritis secondary to congenital malformations of the lumbosacral junction or as the sequelae of trauma are frequently associated with a clinical picture of pain sufficiently intense to lead to lasting disability.

4. Radiography on the Seat. Colleau (40) reported on the results of studies carried out in 1966 by Delahaye and Shickele, who investigated the vertebral changes produced by the flying position in helicopters. A mock-up of an Alouette II was installed in a radiodiagnostic room. The results obtained, while confirming the value of the comfort angles derived by Wisner (246, 247), emphasised that deviations are sometimes increased in the sitting position.

The indictment of these changes of posture in helicopter pilots can only be sustained if they gradually increase under the influence of the flying position, or if they are absent on the control radiograms.

Complementary studies are now in progress.

6.1.3.2. Thoracic Spine

Discrete signs of thoracic arthritis, characterised by anterior marginal osteophytosis without change in the height of the interspaces, are frequently found on radiographic examination of pilots over the age of 40. Their relationship with helicopter flying is not clear, and should be the object of extended studies over a period of time.

6.1.3.3. Cervical Column

Radiological manifestations (anterior marginal osteophytosis, narrowing of the interspaces, deformation of the unciform processes) often occur before the age of 40.

It is now accepted that cervical arthritis represents an anatomical and radiological entity of which the early appearance and the high frequency above the age of 40 (50% of the population) contrasts with a clinical picture that is often absent or more or less intermittent. However, the presence of identical radiological signs in all the pilots examined, of whom the greater number had not reached 40 years of age, should be noted.

6.1.4. Development of Backache in Helicopter Pilots

This depends on several factors:

- the frequency of flight

- the type of mission.

6.1.4.1. Doctor P.N. (a flight surgeon) observed the correspondence between patterns of flight and thresholds favourable for the appearance of painful symptoms:

- more than 4-5 hours flight a day

- more than 2 hours of continuous flight

- more than 40-50 hours flying per month.

There are large variations related to age and to aircraft type.

6.1.4.2. The Type of Mission Plays a Part

Sliosberg (220) reported the case of pilots providing helicopter transport for commando troops involving 8 hours of flight with 50 landings and take-offs. American observations in Vietnam stress the role of repeated landings in combat zones, and also of ground strafing missions in flight at very low altitude, which adds very severe oscillations to the vibrations of the helicopter.

Allouette pilots, working from aircraft carriers to monitor the catapulting and landing of aircraft, match the speed of the helicopter with that of the vessel, which moves at 20-30 knots. These rescue flights, of variable duration, generate vibrations of high amplitude. As the number of such flights increases, the threshold for the appearance of pain decreases, usually after about an hour of flight. Winching exercises and anti-submarine warfare exercises involve hovering flight lasting from 5-25 minutes. The vibration levels are particularly high (40).

If frequent flights are made over a prolonged period, and the cruise of an aircraft carrier involves many rescue missions, backache is only one of the signs of the syndrome of fatigue described by Messenard and Terneau (171) and by Leroux (162, 163) in helicopter pilots. Disorders of sleep, asthenia and changes of arterial blood pressure are also seen in this condition.

After a long period of exposure, a true chronic disorder develops, in which the pain arises earlier in the flight and persists for longer after its end. Extended rest and holidays alleviate the painful symptoms, and may even cause them to disappear. They often

reappear after another helicopter flight.

The symptoms change their character (intensity, time of apperance) if the pilot changes to another aircraft type. For example, pilots report greater comfort on going from the Alouette to the Super Frelon.

The plight of pilots should not allow that of other members of the crew to be forgotten. They are subjected to the same vibrations, and their duties often require them to work in a sitting position leaning forwards. The flight engineer in the Super Frelon, sitting on a folding seat, sometimes suffers quite severely. The engineer in the Alouette is particularly cramped during a rescue mission. During submarine search missions, the sonar operator, who is stationary for a long time, frequently complains of acute pain.

6.1.5. Pathogenesis

Backache in helicopter pilots is due to the synergistic action of two factors:

- postural factor; the poor flying position

- a microtraumatic mechanical factor due to the vibrations of the helicopter.

6.1.5.1. The Postural Factor

Well described by Sliosberg (220, 222), this postural factor is due to the constant and co-ordinated use of all four limbs in helicopter flying. The right arm operates the cyclic pitch control, which is responsible for movement in translation. The left arm operates the collective pitch lever, which controls the lift. The feet operate the rudder bars which, through the tail (anti-couple) rotor, turn the helicopter and allow the flight heading to be selected. The siting of the collective pitch control forces the pilot to bend to the left while the requirements of flight visibility necessitate forward flexion of the trunk with the head in hyperextension.

1. The Lower Limbs

The feet rest on the rudder bar with the lower legs and thighs slightly flexed. Because the aircraft has a tendency to deviate spontaneously to one side, the correction applied by the tail rotor requires constant asymmetric pressure on the rudder bar. Sometimes the pilot, who sits in the right-hand seat, can support his left leg on the control column situated between the two seats. The right leg has nothing to rest against, and this results in asymmetric contraction of the two lower limbs, affecting the posture of the pelvis and, thus, of the lumbar spine.

2. The Upper Limbs

The right arm operates the cyclic pitch control situated between the legs, the elbow being flexed almost to a right angle. In current aircraft, the design of the column allows the right elbow to rest on, and be supported by, the right thigh. In other aircraft (type H134) this control is too high and the pilot must often hold it with the tips of his fingers to achieve a comfortable position. Finally, the control column must be pushed in the direction of flight, which is almost always forwards. This entails forward displacement of the right shoulder.

The left hand operates the collective pitch lever and is semi-flexed without exerting any effort, changes in the position of the lever being assisted by the servo-controls. Nevertheless, this constant posture is characterised by a turning and bending of the left shoulder downwards. In older aircraft (H34), the left hand controls a large collar (the throttle) which leads to constant movements in supination. He must note the handicap imposed upon short pilots, who must adjust their seat to a high position to increase their visibility. For this reason, the distance which separates them from the collective pitch control is greater, and the forward inclination and lowering of the left shoulder are even more pronounced.

3. The Spine

In theory, the thoracic and lumbar spine should be firmly held against the seat back by the straps of the restraint harness. In practice, the need for continuous visibility in flying forces the pilot not to tighten the suspension straps on which, moreover, he supports himself, by leaning forward. The back is thus separated from the seat, and the cervical spine is placed in hyperextension. This latter posture is even more exaggerated if the instrument panel of the aircraft is fairly high (H34), or if the pilot is small of stature.

4. Effects of the Unfavourable Posture

The sustained asymmetric position does not permit any relaxation of the spinal musculature. This plays a significant role in the development of backache.

Sliosberg (220, 222) lists three basic causes for backache:

- unchanging posture

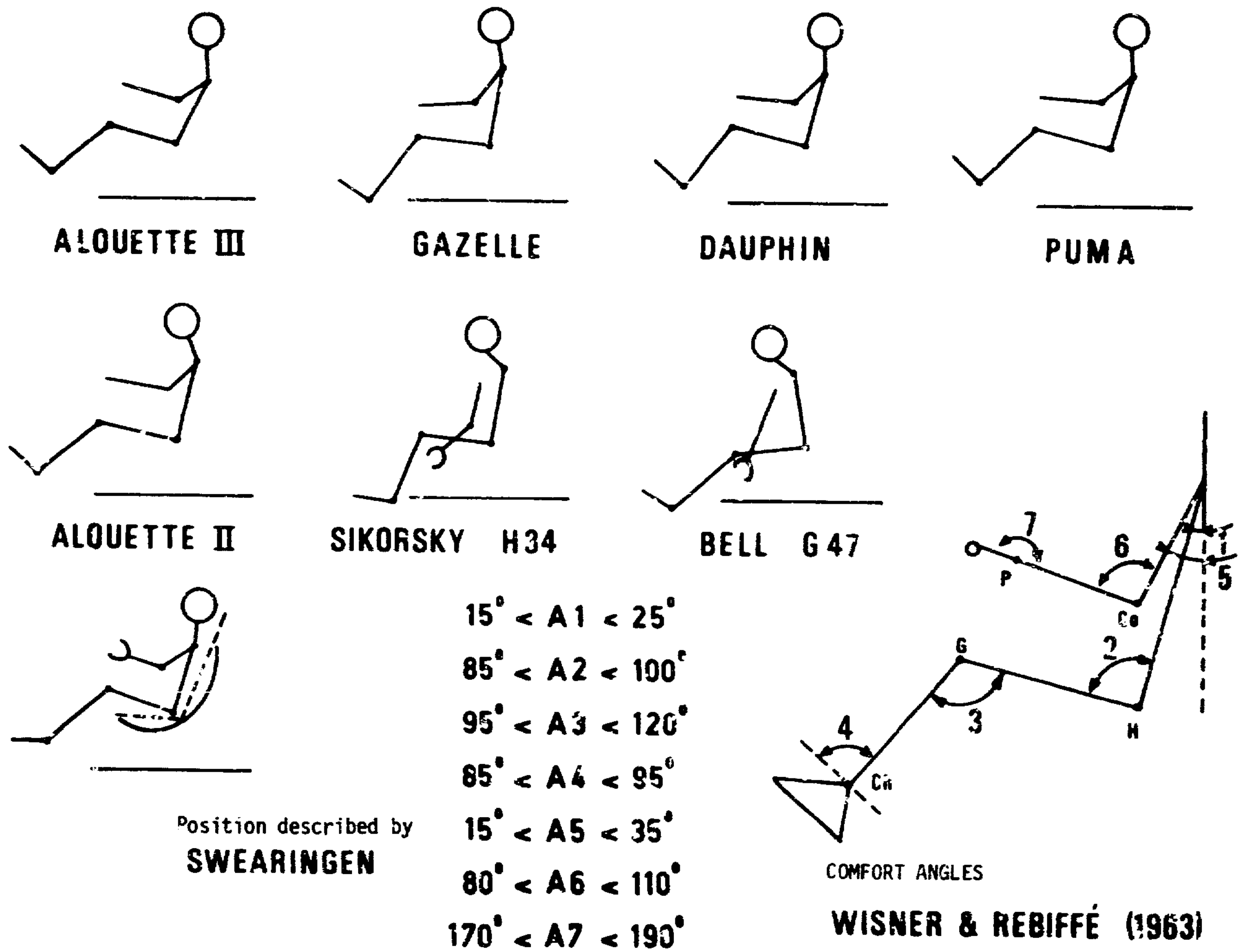


Figure 167. Angles of various body segments, measured in a pilot seated in the cockpit configuration of different helicopters (CEV; Bretigny-sur-Orge)

- asymmetry of posture

- sustained tension in the supporting muscles of the spine.

a. Unchanging Posture

The four limbs are continuously employed to manipulate all the controls. The positions of the latter vary depending upon the phase of flight, but must always be held constant by the pilot, who must remain watchful but immobile. No relaxation is possible from take-off to landing. This is entirely incompatible with comfort.

b. Asymmetry of Posture

This leads to involuntary muscular contraction in some segments of the limb, and is irksome. The spine is tilted laterally, in a most unfavourable posture which greatly increases its sensitivity to the vibrations of the aircraft. This state is exaggerated in landing, take-off, hovering flight, and at low speeds (small degrees of pitch) which are phases of flight where the levels of vibration are especially high.

c. Sustained Tension in the Supporting Muscles of the Spine

When the back and lumbar region are not properly pressed against the seat back, their support is taken over by the perispinal muscles, which are then in a state of permanent contraction.

Rabischong, Seris et al (188) distinguish between static and dynamic seated positions. In the first case, the seated subject seeks a comfortable posture. In the second, the subject must work on a seat which forces various constraints upon him, with loss of support for the back and synergy between the supporting muscles and the straps, which leads to fatigue and to painful symptoms (188).

5. Comfort Angles (Fig. 167)

The posture of the helicopter pilot does not conform to the criteria of comfort established by Swearingen and Wisner (246, 247), who defined the angles which must exist between adjacent skeletal segments to allow, in a seated individual, the good relaxation of opposing muscle groups, which is the physiological equivalent to the subjective notion of comfort.

These values differ considerably from those measured in pilots, especially in an old type of aircraft (Sikorsky H34 for example); in more recent types (Dauphin, Gazelle) the posture of the pilot more closely approaches these comfort angles.

6. Role of the Perispinal Muscles and the Disc-Vertebra Complex

In the analogue models described by Haack (122), Dieckmann (79), and Coermann (38, 39), the human body is simulated by an assembly of suspended masses, connected by systems of springs and dampers (intervertebral discs, ligaments, muscles). The muscles play the part of dampers (Figs. 168 & 169), limiting the movement of the skeleton and so protecting the intervertebral discs. In contraction, their efficiency is rapidly diminished by fatigue. This strained shock absorber no longer plays its protective part, and the vertebrae and discs are then directly exposed to the harmful effect of the vibration.

According to Sliosberg (220, 222), two major factors are implicated in the origin of back pain; one muscular and the other mechanical, of disco-vertebral origin.

The Muscular Factor

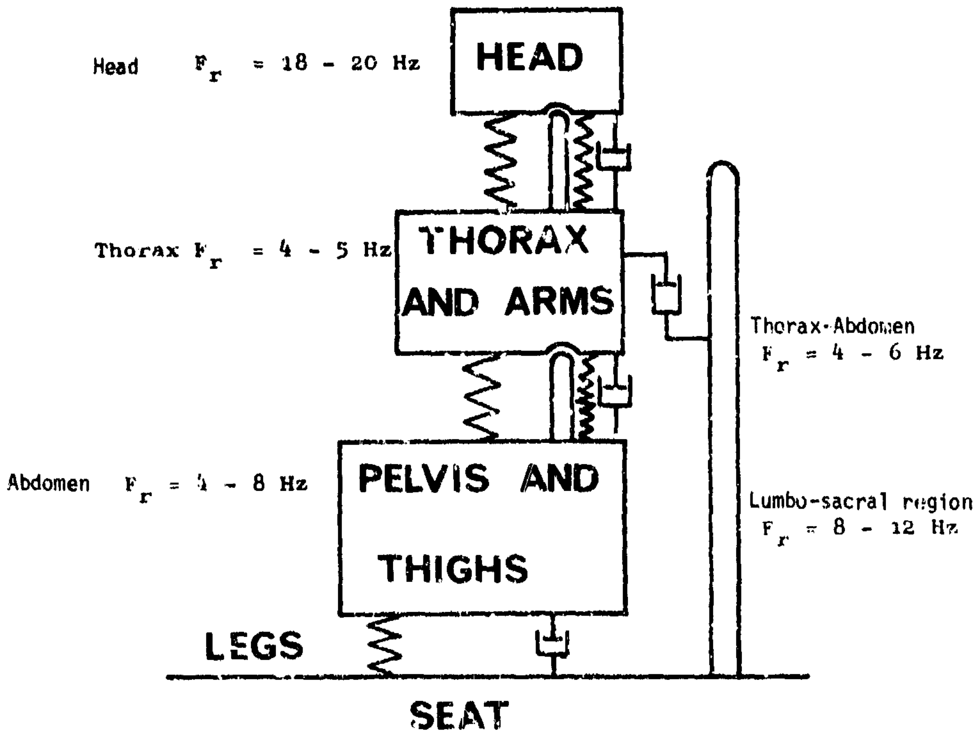
In the statics and the dynamics of the spine, the muscles play an important role as anchors. These sustain the equilibrium of the spine and its movement; when a muscle fails or, conversely, when it goes into contracture from prolonged sustained effort in tension, the equilibrium of the system is lost. Thus, the muscles can be a source of pain.

Disc-Vertebra Mechanical Factor

Keegan (147), in studies of the effects of changes to the lumbar curvature in the seated position, stressed the influence of the angle between the trunk and the thighs in the genesis of lumbar pain. In the sitting position the lumbar lordosis is abolished, the vertebral bodies tend to be closer together in front, and an increase in hydraulic pressure develops in the anterior part of the intervertebral discs. The nucleus pulposus is displaced towards the rear of the intervertebral space, where it can irritate the ligaments or even the nerve roots with which it comes into contact.

The case of pilots in the Naval Air Service, reported by Colleau (40), is particularly interesting.

These pilots, the majority of whose missions require them to fly over the sea, carry survival equipment comprising a Mae West and a back-mounted dinghy. Specifically, the dinghy, which is deflated and folded, has the form of a parachute pack and as such is mounted on the back by suspension straps. It weighs 7-8 kg. To its lower part is attached a CO_2 inflation bottle, which impinges upon the lumbar region of the pilot seated at



F_r = Resonance Frequency

Figure 168. Mechanical model of the seated man (from Haack, 140).

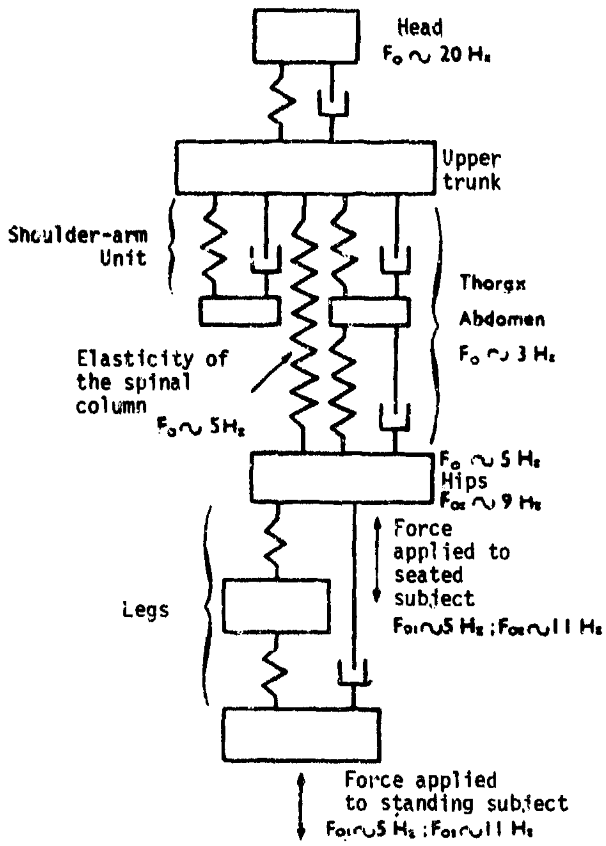


Figure 169. Analogue model of standing or sitting man subjected to vibration Gz $\pm$. Fo = natural frequency (Coermann, 38 & 39).

the controls. Thus, the dinghy acts as a very hard and uncomfortable seat back. The CO_2 bottle and possibly a badly-packed dinghy compress the soft tissues and the vertebral musculature. The impression of wearing a straight jacket is further increased by the weight of the Mae West - 4 kg.

According to Colleau (40) this equipment causes an increased load on the spine and pressure on the intervertebral discs. It also leads to excess work and tension in the paravertebral musculature. Moreover, the seats used in production aircraft were not designed with this assembly in mind. The pilot finds himself in a thrust-forward position (because of the thickness of the dinghy), which reduces the area of support offered by the cushion to the pelvis and especially to the thighs, which are effectively no longer supported, particularly in the case of the small seats of the Alouette.

6.1.5.2. Vibration (General)

Various results from the imperfect function of any mechanical moving system and, like heat, represents a degraded form of energy which the human operator at his work station experiences as a nuisance. The universal character and ergonomic importance of vibration explains why many workers have tried to determine its physiological and pathological effects (38, 39, 79, 246, 247, 248, 24, 25, 26).

The domain of aviation is far from exempt from vibration stress; especially the helicopter which, of all methods of transport, is among those which induce the highest level of vibration. Major efforts have been devoted to the measurement of these phenomena and to the study of their action on aircrew. Among them may be cited those of Goldman (180, 190), Von Gierke (103, 104, 105) and Guignard (118, 119, 120) and, in France, those of Seris, Auffret and their collaborators (207-213).

At the Aerospace Medical Laboratory at Bretigny, tests are currently in progress to study the biodynamic and biophysical effects of these vibrations on man, and to develop solutions for protecting pilots and for increasing their comfort (184, 185, 186).

6.1.6. The Sources of Vibration in Helicopters

6.1.6.1. General

The vibrations recorded in helicopters have two origins; mechanical on the one hand and aerodynamic on the other. They may be described in the classical system of rectangular reference co-ordinates (X, Y, Z) in relation to the human skeleton.

6.1.6.2. Vibrations of Mechanical Origin

Essential for hovering flight, the helicopter rotor has the disadvantage of creating a severe vibratory environment, especially during translational flight. These vibrations have multiple effects on the behaviour of many components and systems of the helicopter.

We shall consider in turn the function of the rotor in hovering flight and in translation, and then the vibrations produced by the main rotor and the tail rotor.

1. Function of the Rotor in Hovering Flight (192) (Figs. 170-175)

The helicopter is in hovering flight when the lift generated by the rotor (Fn) equals the weight of the aircraft. Lift is created by the pressure difference between the two surfaces of the disc rotor; $Fn = S\ (P2 - P1)$

The lift of the rotor is also the sum of the lift forces of all elements of the blades. Each blade element is an aerofoil section driven at a uniform speed U, proportional to the speed of rotation, ω, of the rotor and the distance $d\omega$ of the element from the centre of the hub; $U = \omega \times d$ (Fig. 170).

Pitch is the angle of the aerofoil section with respect to the plane of rotation of the rotor (Fig. 171).

Incidence is the angle which the reference chord of the aerofoil makes with the displacement through the air (aerodynamic speed). When the rotor generates lift, the incidence is different from the pitch (Fig. 172).

The magnitude and direction of the aerodynamic resultant depends on the angle of incidence. This resultant can be resolved into a drag force parallel to the velocity, and a lift force perpendicular to the velocity (Fig. 173).

The lift of a wing section is proportional to its surface area (S), to the density of the air (P), to the square of the velocity of displacement, and to the coefficient of lift of the aerofoil (C_z):

$$Fz = {}^1/_2 PSU^2C_z$$

The lift coefficient C_z varies in an almost linear fashion with incidence, except in the region of the stall (Fig. 174).

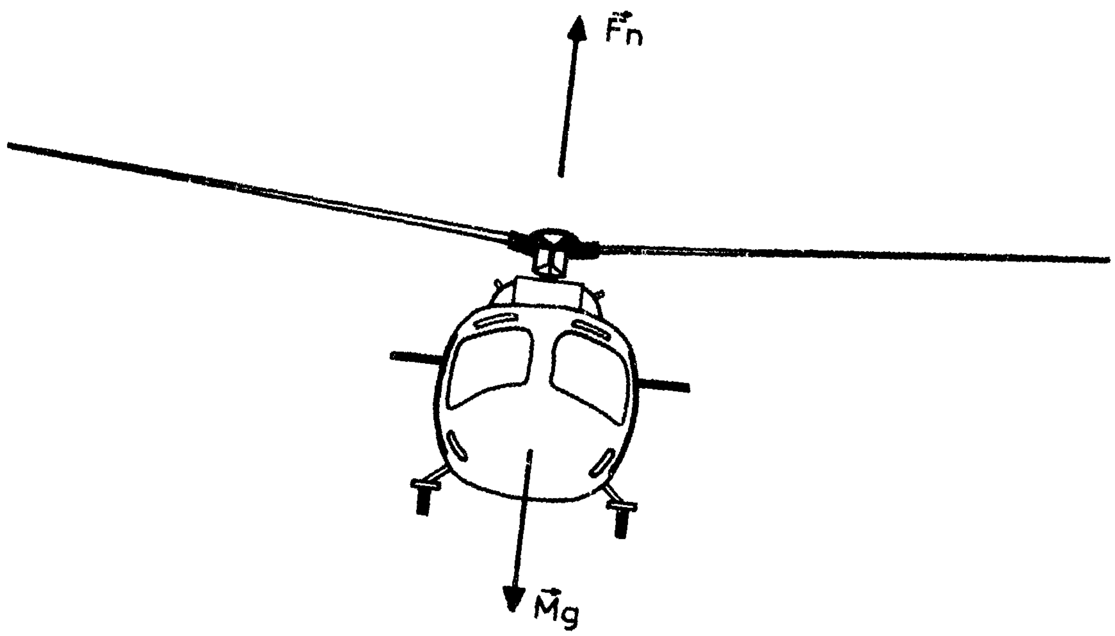


Figure 170. Helicopter in hovering flight (from Richard).

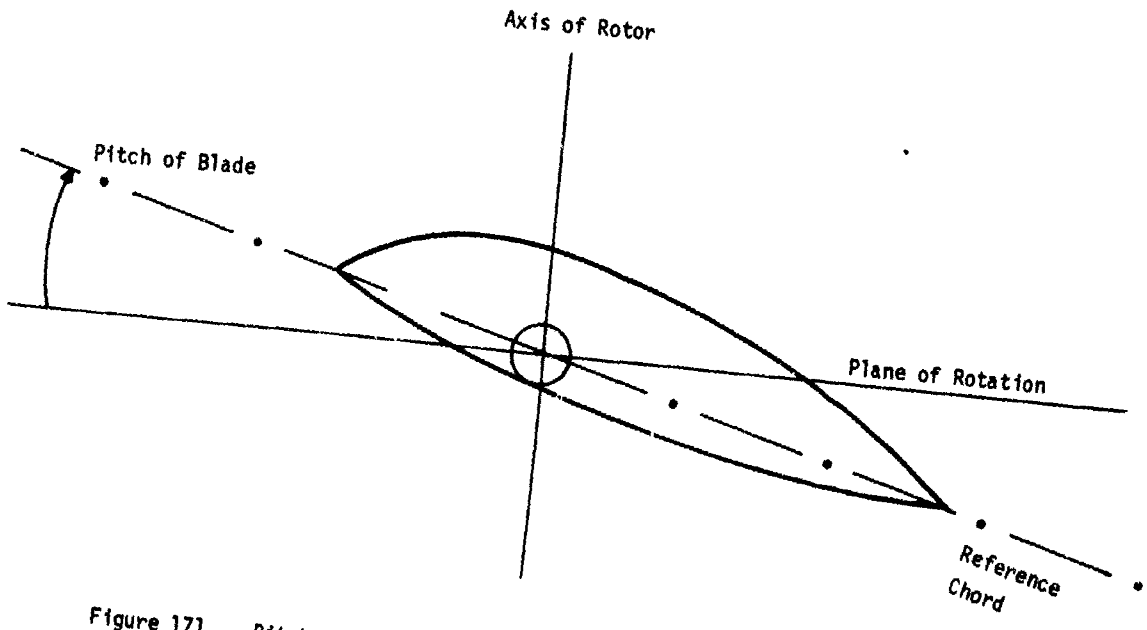


Figure 171. Pitch of blade, axis of rotor and plane of rotation (from Richard).

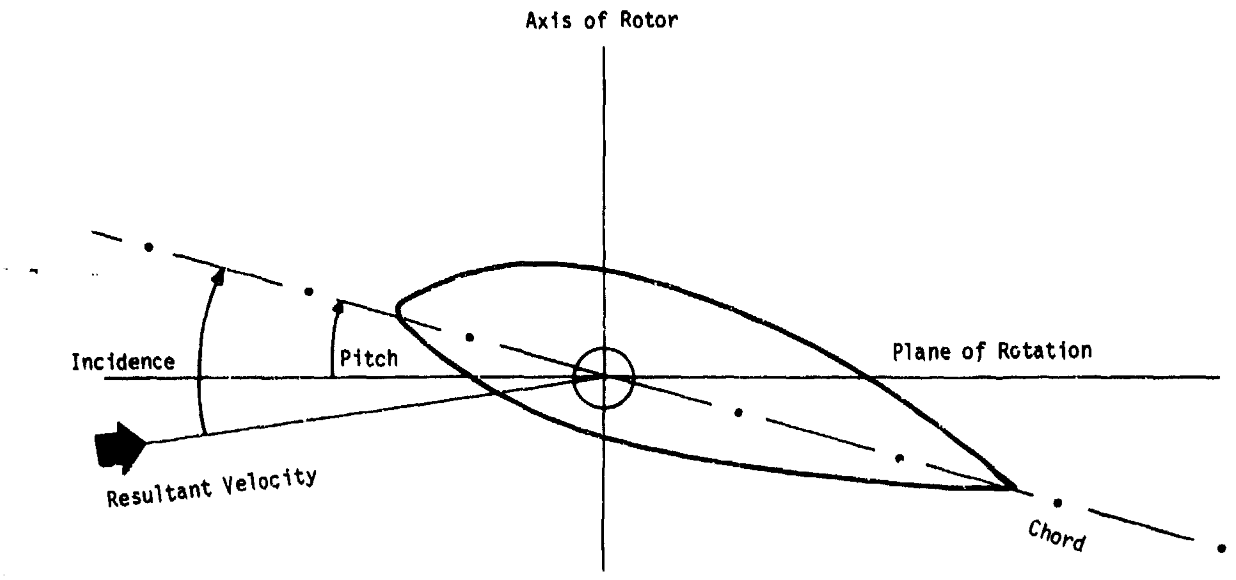


Figure 172. Rotor in hovering flight (from Richard).

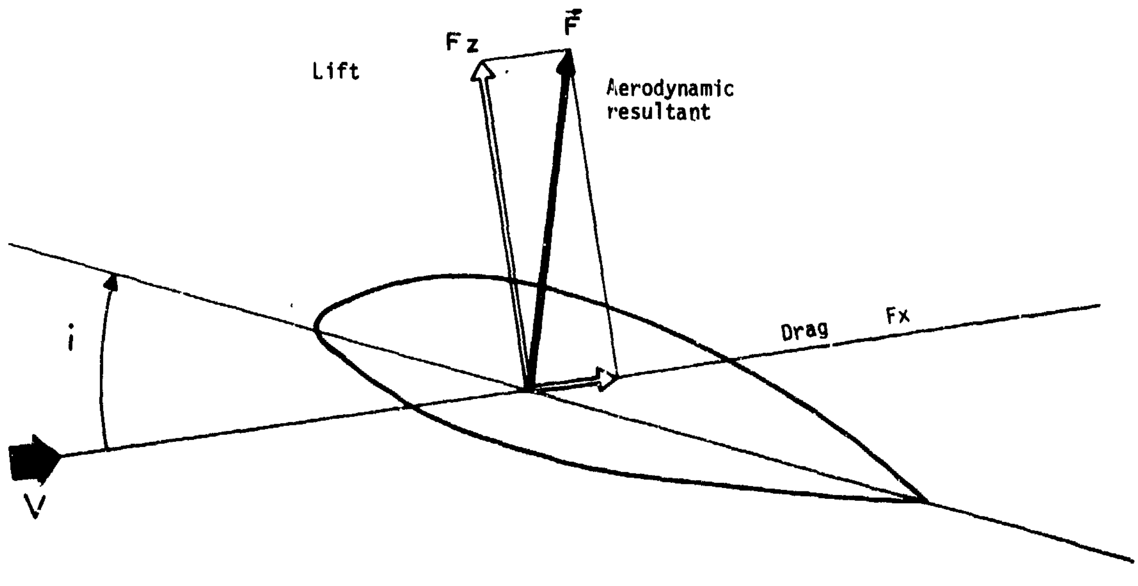


Figure 173. Rotor in hovering flight (aerodynamic resultant) (from Richard).

Because of the flapping hinge, which allows a certain coning angle (a), and of its offset (d) with respect to the axis of the rotor, the effective suspension point of the rotor is situated well above the hub, at the focus of the rotor (hf) (Fig. 175).

In the absence of maladjustments, the centre of gravity of the rotor and the suspension point are on the axis of rotation. For these reasons the vibration level is generally low in hovering flight.

It must be noted, however, that hovering flight close to the ground can produce vibration by the "ground effect", that is, turbulence due to motion of the air set in movement by the blades.

2. The Rotor in Translational Flight (J. Richard)

Asymmetric Lift

When the helicopter is in translational flight, the speed of advance V of the centre of the rotor is added to the speed of rotation of the blades U (Fig. 176). The "advancing" blade has a resultant speed U+V, while the "retreating" blade has a speed U-V. With a rigid rotor, the lift of the advancing blade increases and that of the retreating blade decreases.

The Requirement for a Flapping Hinge

The use of deformable rotors (articulated or flexible) allows the blades to flap. The flapping hinge allows the blade to rise or fall with respect to the drive plane. The angle B is the flapping angle of the blade, and its mean value Bo represents the coning angle of the rotor (Fig. 177).

Each element of the blade is in equilibrium between the lifting, centrifugal and inertial forces. The centrifugal force being constant for a given rotor geometry, the flapping angle depends essentially on lift (Fig. 178).

It follows that the hub compels the rising blade to follow a longer path (DB) than that corresponding to its own rotation (DC). For a rigid rotor turning at constant speed, the tip of the blade is thus constrained to accelerate with respect to its virtual axis of rotation, which imposes upon it a large variation of kinetic energy and a considerable flexing moment. It is possible to suppress these disadvantages by articulating the trailing blade. During rotation, this lags with respect to the hub so as to reach C with conservation of its peripheral speed and thus a constant kinetic energy. Naturally, the converse applies when the blade descends.

Unlike the flapping movement, oscillation in drag is imperfectly stable and must be braked by a drag damper (Fig. 178).

3. Vibrations Caused by the Main Rotor (Figs. 179 & 180)

The movements of the blades in flap and in drag at the rotation frequency of the rotor subject the hub to periodic forces in the vertical and horizontal planes, with a frequency of ω (1 per revolution) and $b\omega$ (b = number of blades). These forces are transmitted to the airframe by the hub.

These phenomena are further complicated by deformation of the blades. In fact, if the forces acting on each element of the blade are analysed step by step, it is found that each blade is deformed on each revolution relative to its azimuth.

The flapping hinge thus allows the blade to rise as its lift increases and to fall as it decreases. The speed of rise or of fall is proportional to the angle of the hinge. The speed of flapping is compounded with the resultant velocity of the blade: U+V, to give the true incidence of the blade element.

As the blade rises, its angle of incidence decreases, which allows equalisation of lift and annuls the roll couple which the asymmetry of speed tends to induce. It must be noted that the speed of rise is maximal broad-side on to the helicopter; thus, the blade occupies its highest position in front and its lowest behind the disc (for these positions, the speed of flapping is zero). The rotor is accordingly tilted towards the rear with respect to its drive plane.

The flapping motion is stable, because the blade, which is in equilibrium about its flapping hinge under the influence of lift, centrifugal and inertial forces, only rises and falls to the extent strictly necessary for the equalisation of lift.

Requirement for a Drag Hinge

Because of the flapping movement, the helicopter flies with a warped rotor, the virtual axis of rotation of being displaced with respect to the true axis of rotation.

This means that with each revolution the blade is periodically forced into flexion, with alternating stresses which can be very large in some flight conditions (transitional flight at high speed, turns, or recovery from a dive).

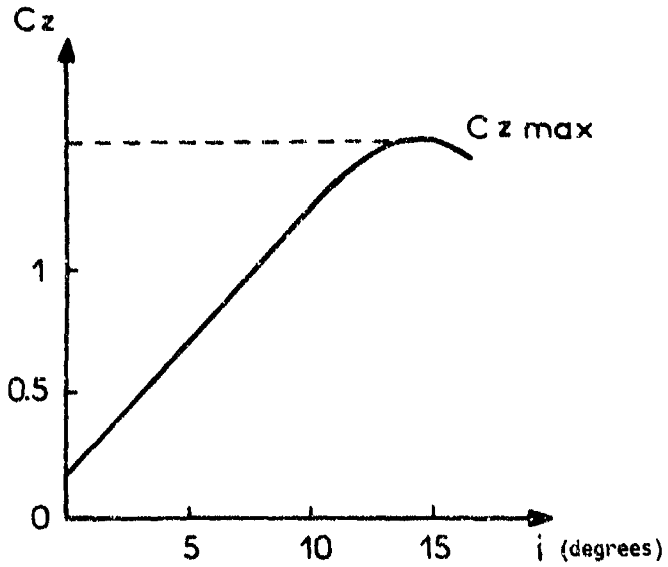


Figure 174. Variation of lift coefficient with blade incidence (from Richard).

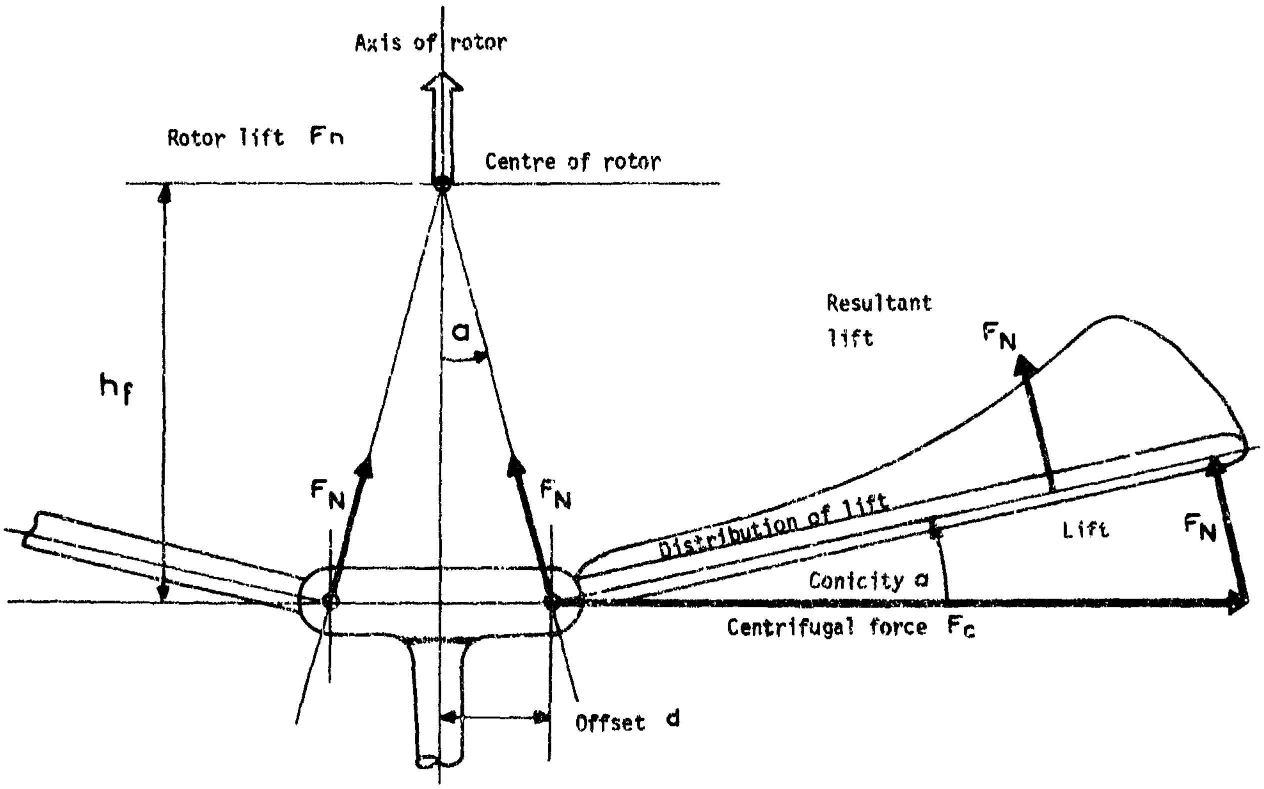


Figure 175. Rotor in hovering flight.

Distribution of lift (from Richard)

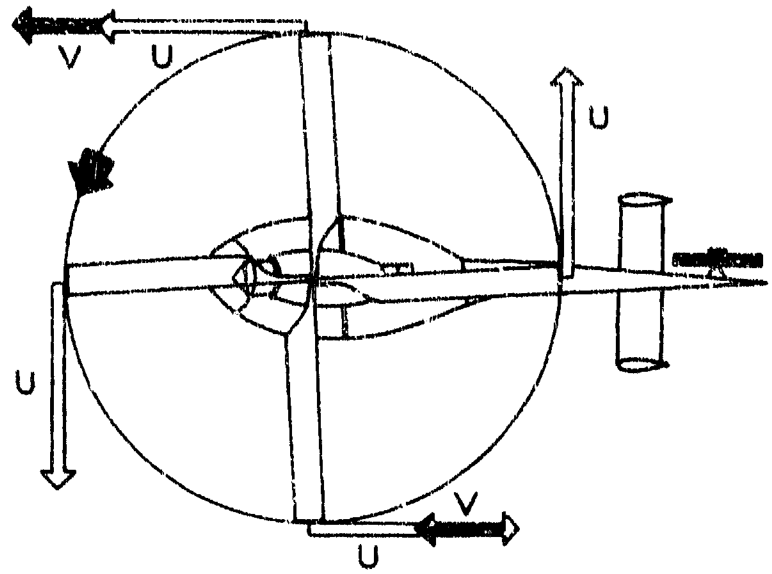


Figure 176. Translational helicopter flight (from Richard).

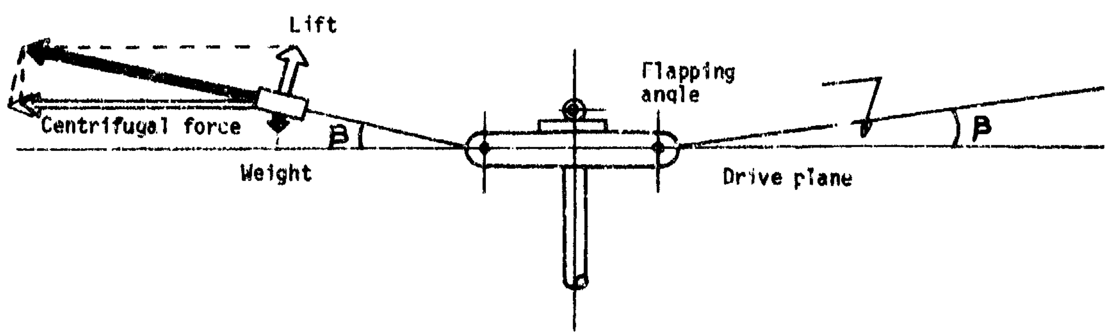


Figure 177. Articulation of flapping hinge (from Richard).

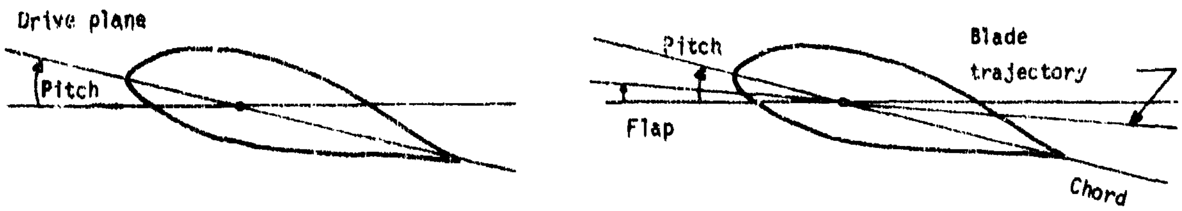


Figure 178. The flapping of the rising blade (right) reduces the angle of attack (from Richard).

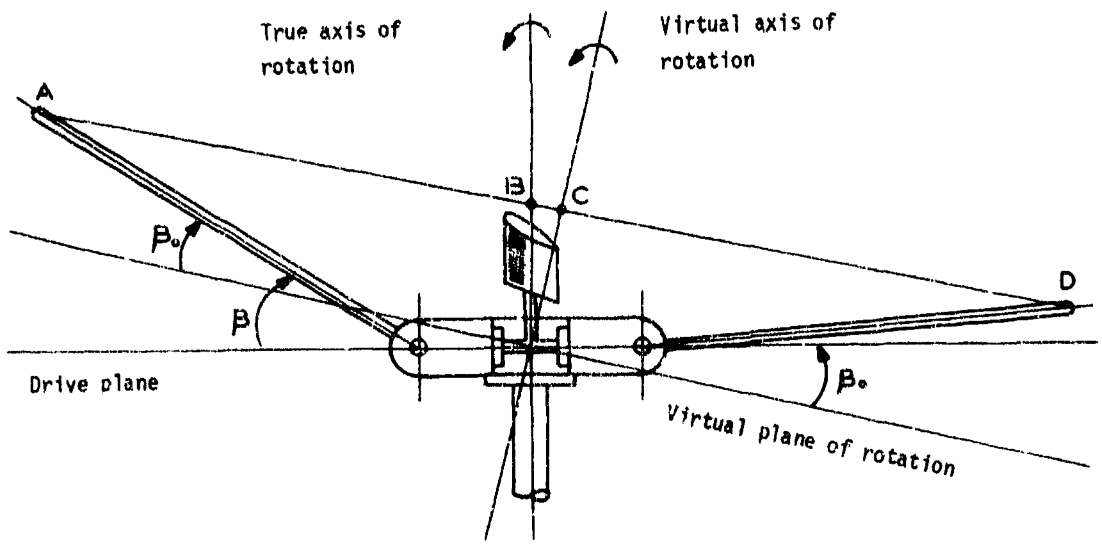


Figure 179. Axes of rotation in a helicopter (from Richard).

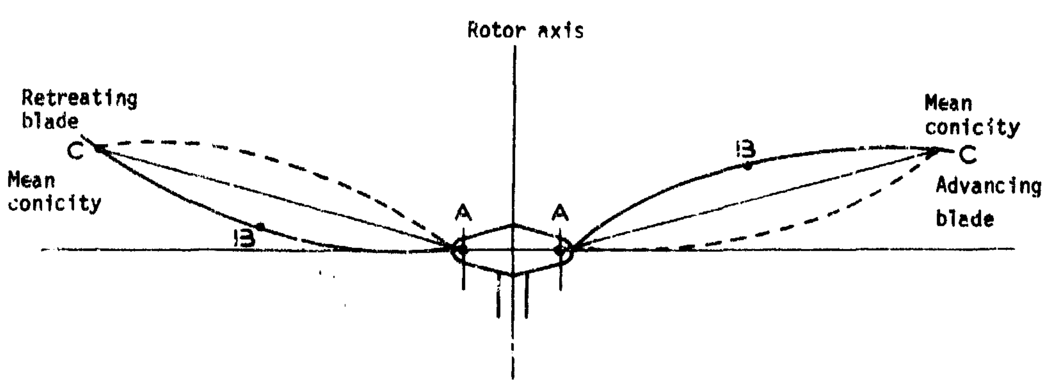


Figure 180. Mean conicity of advancing and retreating blades (from Richard).

In fact, as the forward speed increases, other phenomena arise, which augment the deformation of the rotor and are a supplementary source of vibration. They include stalling of the retreating blade with the existence of a region of reversed flow, and compressibility phenomena on the advancing blade.

To the "natural" vibrations which we have just discussed must be added vibrations due to maladjustments, to imbalance, or to wear of the blade profile by erosion. These faults are almost always manifested by a significant increase in the level of vibration, most often at a frequency of ω but also sometimes at frequency $b\omega$.

4. Vibrations Produced by the Tail Rotor

The tail rotor operates in conditions to those very similar to the main rotor, and it is therefore natural that it should also generate periodic horizontal and vertical forces which further degrade the vibration environment of the helicopter. It must also be noted that because the tail rotor is usually of modest size, the manufacturers omit drag, and even flapping, hinges. This involves a system with distributed deformations (flexible blades and hubs) which do not fundamentally change the action of the rotor compared with mechanical flapping and drag hinges. These "rigid" rotors are, however, quite difficult to produce and generally led to an increased level of vibration. This is equally true for most "rigid" main rotors.

5. Other Sources of Vibration

The passage of part of the rotor or of the airframe through the wake of another element can excite low frequency aerodynamic vibration (buffeting).

All the rotating elements - and they are many (engines, gears, transmission shafts) - are liable to produce excitatory forces at the frequency of rotation or its harmonics. Proper balancing of these elements generally allows these to be reduced to an acceptable level.

In summary, vibrations of mechanical origin are of low frequency and are caused by the main rotor turning at its own frequency, and by the blades of that rotor.

The main causes can be:

- the operation of hinged devices (cyclic pitch, flapping); these are related to the design of the aircraft itself, and they produce vibrations of frequency $b\omega$, principally in the Z axis (seat-head)

- the difference in drag between the advancing and retreating blades

- poor regulation of the incidence of one blade with respect to the others, leading to vibration of frequency ω in the Z axis

- possible defects in the static equilibrium of the blades (imbalance) which creates an oscillation of frequency ω in an axis perpendicular to the preceding one.

Finally, to these must be added high frequency vibrations which have as their origin:

- the operation of the engines or turbines

- the rotor (frequency ω) and its blades (frequency $b\omega$)

- the moving parts in the transmission system.

6.1.6.3. Vibrations of Aerodynamic Origin

Of very low frequency, these are due to the responses of the airframe to aerodynamic excitation and to the actions of the pilot through the servo-controls (Seris, Auffret). They become important in manoeuvres at high or low speed, during flight over rough ground at low altitude or in hovering flight close to the ground.

6.1.6.4. Measurement of Vibrations and Acceleration Characteristics

Vibration can be characterised by measuring its frequency and its amplitude (displacement or acceleration). In the case of the helicopter, the technique is critical, because the spectrum of frequencies is very wide and the vibratory modes of the airframe are numerous. The information has no value without knowledge of the site where the measurement was made, the axis (X, Y or Z), the frequency of interest, and the units of measurement.

Measurement of vibrations by spectral or frequency analysis, which give the distribution of energies as a function of frequency, has been carried out at the Flight Test Centre for different types of helicopters; it has allowed the determination, for each aircraft, of two characteristic low frequency peaks corresponding to 3.7-8.5 Hz and to N (15-22 Hz).

While the first peak, which is due to maladjustment, can be considerably reduced, the second is an inherent function of the helicopter itself and is unavoidable.

The response of the human body to these vibrations can be evaluated in flight by means of accelerometers attached to the seat and to the major body masses. It can also be studied in the laboratory on vibrating tables. The Aerospace Medical Laboratory has an electrohydraulic vibration generator which can be energised either by a regular (sinusoidal) wave form, or from a magnetic tape reproducing the vibrations recorded on-board the aircraft.

6.1.6.5. Subjective Evaluation of Vibration Levels

To reduce the difficulties associated with interpretation of measurements, the Flight Test Centre at Bretigny requires its test flight crews to evaluate the vibration level of each new aircraft. To do this, each crew member separately assigns a value from 0 to 10 for each configuration of flight.

The evaluation scale used jointly by the Flight Test Centre at Bretigny and the Armament and Aeronautical Experimental Establishment at Boscombe Down classifies the different levels of vibration in terms of the discomfort experienced during a mission (Table 6.2).

TABLE 6.2

0		The helicopter does not vibrate.
1 2 3	Slight vibration	Aircrew engrossed in the mission do not notice the vibration, but it is detectable if brought to their attention or if they are not fully occupied.
4 5 6	Moderate vibration	Aircrew are conscious of the vibration, but it does not interfere with the performance of the mission, at least in short-term.
7 8 9	Severe vibration	Aircrew feel the effects of the vibration immediately, even if they are engrossed in the mission. Efficiency is reduced, and some tasks can only be performed with difficulty.
10	Intolerable vibration	The sole pre-occupation of the aircrew is the reduction of the level of vibration.

6.1.6.6. Scale of Assessment of Vibration Levels in Helicopters (Table 6.2)

The assessment criterion is an operational one; the crew determines the effect of the vibration on the execution of the aircraft mission.

A score of 6 represents an acceptable aircraft; a score of 7 an unacceptable one.

With some experience, the results obtained are remarkably consistent. Some variation exists, because some test personnel are more critical or more sensitive than others, but it is relatively small at the end of a flight when all configurations have been studied. This method allows an evaluation of vibration level as a function of speed, of power setting, of load or of any other parameter to be obtained quickly and without instrumentation. It is particularly useful for the quick assessment of the effect of a modification.

6.1.7. Results of Vibration Measurements in Helicopters

6.1.7.1. Physiological Effects of Vibration

These are caused by the deformations and displacements to which organs or tissues are subjected at certain frequencies.

The studies of Diekmann (79), Haack (122) and Coermann (38, 39) have, with the aid of simple analogue models, facilitated the study of the effect of vibrations in the Z axis on the body, and more particularly on the spine.

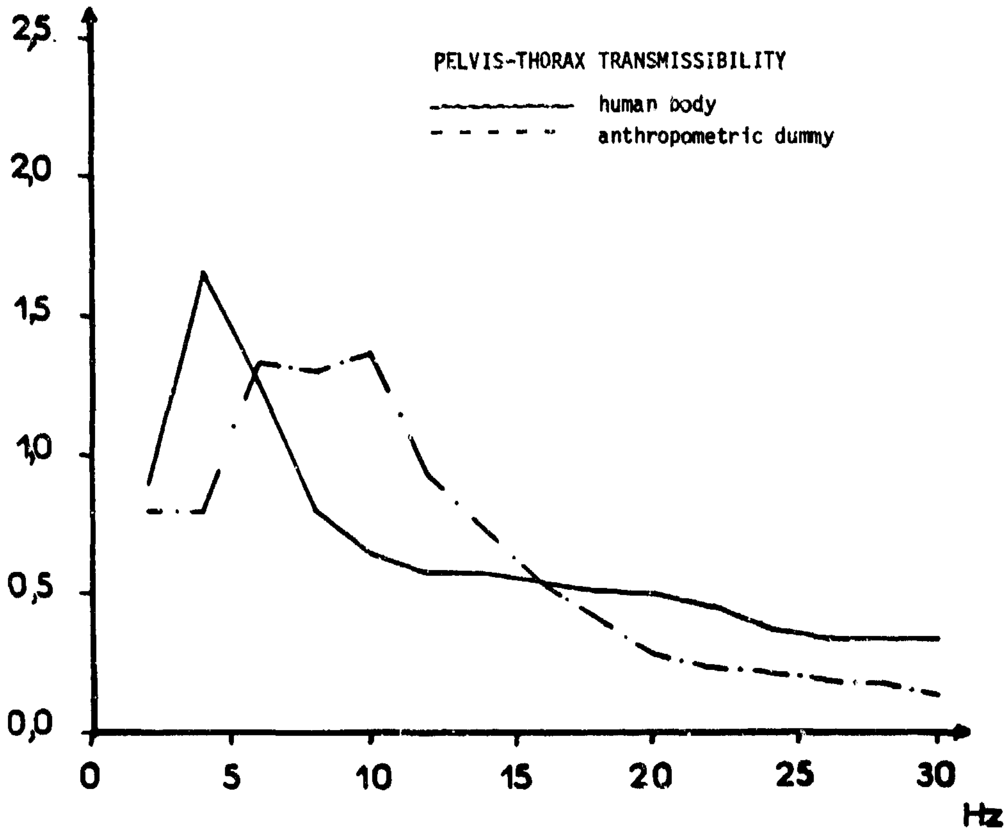


Figure 181. Comparison of transmissability of vibration for the human body and an anthropometric dummy.

abscussa - frequency (Herz)
ordinate - pelvis-thorax acceleration ratio

(from Poirier, 184)

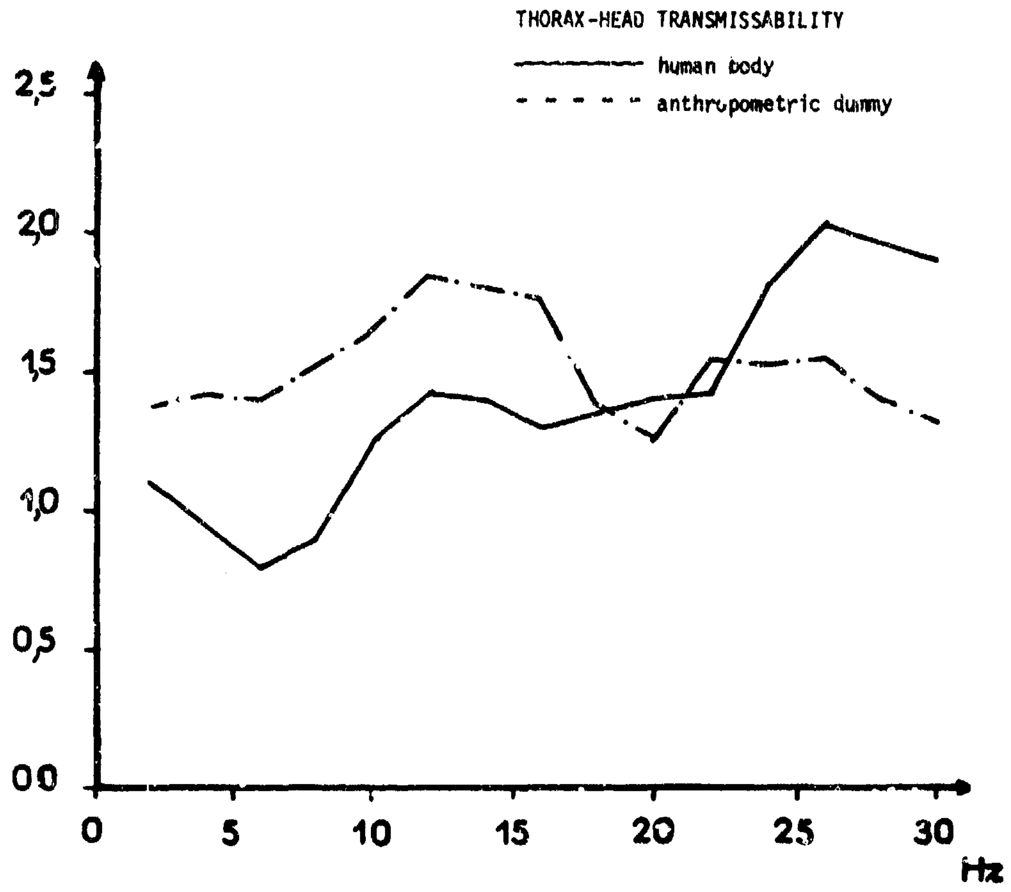


Figure 182. Comparison of transmissability of vibration for the human body and an anthropometric dummy.

abscissa - frequency (Herz)
ordinate - head-thorax acceleration ratio

(from Poirier, 184)

Each segment of the human body, has a resonant frequency. This is the frequency at which the transmission of motion applied to the supporting structure is at its maximum. Above this frequency, transmissibility decreases; there is a filtering effect.

The physiopathological effects of vibrations depend on the resonant frequency of the different body masses and on the frequency applied to the support.

The resonant frequency for the whole thorax is between 4 and 6 Hz (108, 109); it is 12-14 Hz for the upper part of the thorax with forward flexion of the spine and 20-30 Hz for the head.

Overall, the amplitude of the response is higher than that of the excitation between 2 and 10 Hz. Beyond this it decreases. Between 20 and 30 Hz the head has a vibration amplitude three times greater than that of the adjacent segment.

Using a vibrating platform, Poirier (184, 185) measured the transmissibility between the three principal body masses; the thorax, the pelvis and the head. These models are realistic. Resonances of 3-6 Hz for the thorax and 20-30 Hz for the head were confirmed by measuring the relative accelerations from thorax to pelvis and from head to thorax. Small individual variations were observed, depending upon the individual morphology of each subject.

In helicopters, values of the same order have been found by measurements carried out on board. The eyes vibrate in the head at a frequency between 16 and 19 Hz, and the larynx at 20 Hz, which explains the difficulty of flying helicopters in some manoeuvres.

The mathematical models do not well describe the transmission properties of anthropometric dummies. Poirier found a large difference between dummies and men for sinusoidal vibrations from 0-30 Hz and for constant accelerations at each frequency from 0.3-0.6 G, effectively. There is a discrepancy in the resonant frequencies. For the thorax they range from 4 Hz in the man to 8-18 Hz in the dummy. The transmissibility is also different in the man and the dummy for frequencies between 2 and 30 Hz (Figs. 181 & 182).

The helicopter seat amplifies the vibrations up to a frequency of 10-15 Hz but then tends to damp them out at higher frequencies. This amplification of the low frequencies, which can reach a factor of 2.5, increases the stress on the spine.

6.1.7.2. Measurements in the Super-Frelon (1967)

Seris, Auffret et al (207) have published measurements of accelerations on the seat, the pelvis and the thorax of a Super-Frelon pilot as a function of observed frequency in the standard X, Y, and Z axes.

1. Hovering flight with ground effect

- in the Z axis

  . from 2-11.5 Hz: minimal amplification between the seat and pelvis, with very small acceleration levels; 0.1-0.2 m/sec^2

  . at 20 Hz: damping (by a factor of 2) between the seat (1.2 m/sec^2) and the pelvis (0.6 m/sec^2)

  . at 40 Hz: damping caused by the seat (by a factor of 4) with accelerations of 0.1 m/sec^2 at the pelvis

- in the Y axis

  . at 20 Hz: amplification (by a factor of 2) between the seat and pelvis (1.5 m.sec^2) and damping (by a factor of 2.4) between the pelvis and the thorax (0.7 m/sec^2)

2. In forward transition

- in the Z axis

  . at 20 Hz: damping (by a factor of 2) between the seat (3.2 m/sec^2) and the pelvis (1.5 m/sec^2)

- in the Y axis

  . at 20 Hz: amplification (by a factor of 2.5) between the seat (1.2 m/sec^2) and the pelvis (2.9 m/sec^2)

3. In level flight

- in the Z axis

. at 20 Hz: minor damping between the seat (0.6 m/sec^2) and the pelvis (0.5 m/sec^2)

- in the Y axis

. at 20 Hz: amplification (by a factor of 2.5) between the seat (1.6 m/sec^2) and the pelvis (3.4 m/sec^2).

Vibrations within the resonance range of the human body are not totally absorbed by the seat, even for very low values of acceleration.

The mechanical vibrations at a frequency of 20 Hz lie above the resonance of the human body and are appreciated less. In the Z axis, they are well damped by the seat, while retaining high acceleration levels. In contrast, the seat amplifies those in the Y axis, with quite high accelerations. They thus produce transverse loads on the pelvis of the pilot, with shearing forces on the skeleton, the ligaments and the muscles, the precise effect of which is still unknown.

Overall, these data support the good opinion of the aircraft held by the users. The flying position conforms to the data given by Wisner for comfort angles; the seat is slightly inclined backwards and the controls are well placed, particularly the collective pitch lever. The pilot is not obliged to bend forward and to the left.

6.1.7.3. Measurements from the Puma SA330 (208, 210)

In general, the accelerations measured are much greater and at the lower frequencies the values are quite high. In the Z axis amplification occurs between the pelvis (1 m/sec^2) and the head (1.2 m/sec^2).

1. In level flight at 1000 metres and 250 km per hour

- in the Z axis

. at 8.5 Hz: amplification (by a factor of 3) between the seat (0.8 m/sec^2) and the pelvis (2.5 m/sec^2)

. at 17 Hz: amplification (by a factor of 2.6), attributable to the seat, between the floor (1 m/sec^2) and the pelvis (2.6 m/sec^2)

- in the Y axis, raised levels of acceleration

. 4.4 m/sec^2 at the floor

. 5.3 m/sec^2 at the pelvis

2. Descending at 50 km per hour

- in the Z axis

. at 17 Hz: amplification (by a factor of 2), due to the seat, between the floor (1.2 m/sec^2) and the pelvis (2.8 m/sec^2)

3. At maximum speed (320 km per hour)

- in the Z axis

. at 17 Hz: high values of acceleration at floor level (2.6 m/sec^2), but lower at the level of the head (1.5 m/sec^2).

During turns, the acceleration levels are very high; in the Y axis at 17 Hz 5.6 m/sec^2 and 6.8 m/sec^2 have been measured at the pelvis.

At very low frequencies, the vibrations have high amplitudes and are not damped by the seat. Vibrations of mechanical origin (17 Hz) reach very high levels and are amplified by the seat by a large factor. The absorption provided by the perispinal muscles is inadequate, and the acceleration levels therefore remain elevated at head level. This explains the appearance of visual disturbances noted during the investigation, with inability to distinguish the needle and figures of a fixed display facing the subject, which was easily read at rest and above the frequency band of 15-25 Hz. The frequency of 17 Hz is close enough to the resonance of the human body to be perceptible.

6.1.7.4. Alouette II (1971) (212)

The vibrations are not high, with small accelerations in all frequency ranges, particularly those of interest (0.1 m/sec^2 to 0.5 m/sec^2).

1. In level flight at 85 knots and 1000 metres

. at 18 Hz in the Z axis: amplification caused by the seat, between the floor (0.5 m/sec^2) and the pelvis (0.9 m/sec^2)

. at 18 Hz in the Y axis: amplification between the floor (0.15 m/sec^2) and the pelvis (0.75 m/sec^2).

The highest values are found during autorotation with, in the Z axis, 0.25 m/sec^2 at the floor and 1.15 m/sec^2 at the pelvis.

Although the seat amplifies the vibrations, the levels of acceleration nevertheless remain quite low, and the overall vibration environment of the aircraft can be considered as almost innocuous.

6.1.7.5. Alouette III (1971) (212)

The vibration levels are higher than in the Alouette II, varying from 0.5-1 m/sec^2 . The characteristics of the seat are, on the whole, better except in the following phases of flight, where there is amplification.

- Cruising at 1000 metres

. at 17.6 Hz in the Z axis: amplification (by a factor of 2) between the floor (0.5 m/sec^2) and the pelvis (1.05 m/sec^2)

. at 17.6 Hz in the Y axis: amplification (by a factor of 2) between the floor (0.6 m/sec^2) and the pelvis (1.25 m/sec^2)

- In autorotation

. at 17.5 Hz in the Z axis: amplification (by a factor of 3) between the floor (1.2 m/sec^2) and the pelvis (3.6 m/sec^2)

. at 17.5 Hz in the Y axis: amplificiation (by a factor of 5) between the floor (0.45 m/sec^2) and the pelvis (2.15 m/sec^2).

In summary, although the characteristics of the seat are better than those of the Alouette II, the vibration level is higher. The incidence of pathology is also a little greater.

TABLE 6.3

Vibration Levels - Z-Axis (C.E.V. Bretigny) (75)

TYPE	Alouette II	H 34	Alouette III	Super Frelon	Puma	Gazelle	Lynx	Dauphin
Year of Construction	1955	1956	1959	1962	1965	1967	1971	1972
Engine	Turbine	Piston Engine	Turbine	3 Turbo-Jets	2 Turbo-Jets	Turbine	2 Turbo-Jets	Turbine
Frequency Hz	18	15	17.5	20	17	19	21.7	23.3
Acceleration -g (cruising)	0.2	0.2	0.3	0.1	0.1	0.15	0.2	0.15
Acceleration -g (V.N.E.)	0.2	0.3	0.35	0.1	0.22	0.25	0.4	0.22

6.1.8. Experiments With Seat Cushions

Poirier (184, 185) studied the transmission of vibrations through various helicopter seats and through different cushions on the same helicopter seat.

The transmission factor varies from 1-2 according to the type of cushion or seat.

The vibration levels measured at the pelvis of the pilot are quite high at low or at very low frequencies. Within the range of harmful frequencies, there is a significant amplification between the seat and the pelvis, due to the seat cushion. For frequencies between 1 and 20 Hz, this result is obtained for all types of seats (Figs. 183 & 184).

As Wisner (246-248) and Berthoz (24-26) state, the importance of phase differences between the different suspended masses must be stressed. They are particularly hazardous for the spine; especially phase differences between the thorax and the pelvis. As well as these axial movements, vibrations in the Z axis produce oscillations in the vertebral column from front to back. Between 12 and 14 Hz, for example, the thoracic spine flexes forwards. At the head, horizontal oscillations occur. These fore and aft movements, accentuated by the hyperextended position and by the wearing of a helmet (which adds some inertia to the system), can cause pain. The effect on the spine of the vibrations in the X or Y axis, caused by shearing forces and amplified by the seat cushion, is still poorly-understood.

6.1.9. Methods of Protection

Two objectives must be pursued together: to adapt the man to his work, and the machine to its human operator.

6.1.9.1. Protection Against Vibration

1. Control of Vibration

The control of vibration is the most attractive, but the most difficult, aspect of prevention. While only the low frequencies are of interest to the flight surgeon, all frequency levels concern the engineer, to the degree that they cause structural stress and thus more rapid wear. Thus, any improvement in the vibration level of the aircraft is also valid and beneficial for pilot comfort.

As far as helicopters are concerned, considerable progress has been made in respect of the vibration levels in new generation aircraft. This change has been measured in the Gazelle, and determined subjectively by the pilots in the Dauphin and the Ecureuil, the latest products of the French aeronautical industry. It results from technological improvements, which have allowed articulated metal systems to be replaced by single blocks of plastic material, and the installation of dampers which reduce the vibrations generated by the movement of the rotors and transmission.

Attention must be drawn to the harmful character of low frequencies, and to the fact that reduction in the resonant frequency of an aircraft is not necessarily beneficial. The resonant frequencies of the body lie mainly between 3 and 12 Hz, and care must be taken that the vibrations of the helicopter lie outside this zone. The definition of the resonant frequency of a body shows, in fact, that a change of a few Hz or less can considerably diminish the response. Thus, a difference of a few revolutions per minute in an engine can cause disagreeable flutter.

2. Isolation of the Pilot

If the vibrations cannot be eliminated or greatly attenuated, prevention is attempted by isolating the pilot. This isolation is confined to the seat which transmits and amplifies the vibrations.

- The attenuation of transmissed vibrations is achieved by fitting a special suspension with torsion bars or hydropneumatic shock absorbers. This difficult solution, which entails an increase in weight, is not used in practice.

- Seris and Auffret (210) have shown that the attenuation of vibrations at the pelvis is a difficult problem. The seat cushions damp out vibrations of high frequency quite well, but are ineffective in the range of body resonances, and very often amplify the displacement. The problem lies with the material used to make the cushion. In the construction of a seat this property is altogether independent of the shape that the cushion must have to meet standards of comfort.

Poirier (185) studied different seat cushions designed for the Puma SA330 (Fig. 185). He described a satisfactory cushion providing very significant damping of the vibration. Five types of cushion were compared with the original cushion and a seat was constructed with one of them.

At the lowest frequencies, up to 5 Hz, all the seats behaved in the same fashion. The amplification was maximal at the resonant frequencies of the thorax-pelvis complex and of the seat itself. It seems to be very difficult to achieve much damping at these frequencies.

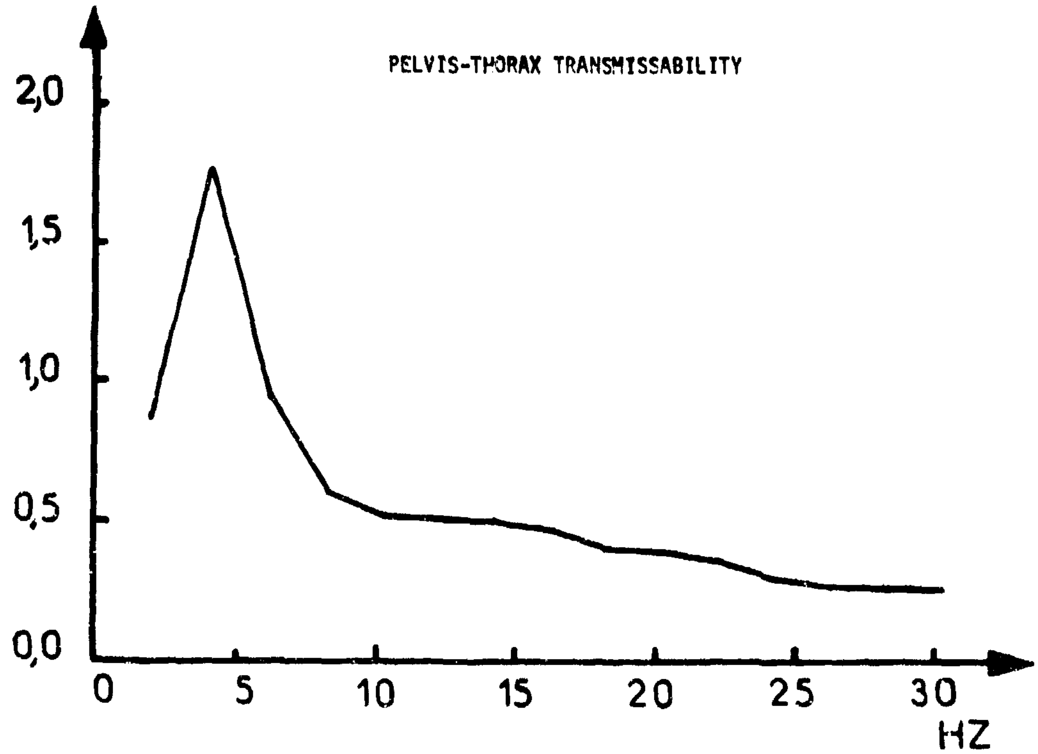


Figure 183. Transmissability of vibrations through the human body (from Poirier, 184).

abscissa - frequency (Herz)
ordinate - thorax-pelvis acceleration ratio

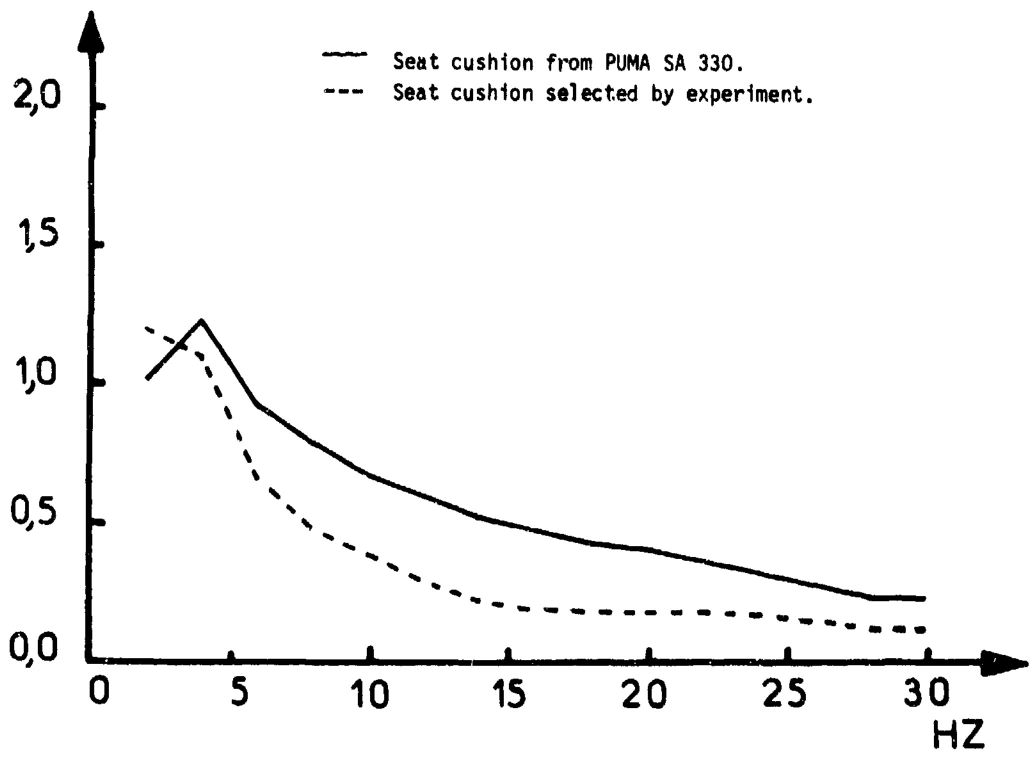


Figure 184. Transmissability of vibration through two Puma SA 330 seat cushions.

abscissa - frequency (Herz)
ordinate - seat-pelvis acceleration ratio

The selected cushion gave a great improvement in the zone of the dominant frequencies of helicopters - 15-20 Hz. At 9 Hz, the vibration level was halved, and this finding was applied up to 20 Hz.

Finally, the ideal solution may be found in the use of "active" systems for isolating the seat occupant. The seat itself vibrates. Sensors detect the bursts of acceleration in all axes caused by turbulence. By means of an electronic and hydraulic system, they transmit different vibrations, which isolate the seat by attenuating the vibrations to which the airframe is subjected. This experimental seat was designed to protect the pilots of combat aircraft flying through turbulence. It could also find application in helicopters, but the system is complex and very heavy, and its cost is also very high.

At present, simpler solutions are being studied. The Association d'Etude pour les Applications des Oscillations Mechaniques (ADOM, Fig. 186) has developed, under the supervision of DRET, a seat mounted on pneumatic dampers. This seat is a refinement of the model patented by Le Forestier. Initial results are quite encouraging. In any event, it represents an interesting avenue of research.

In another approach, SNIAS has studied a multiple foam cushion. It consists of a series of foams of different densities, assembled to distribute pressures rather more uniformly on the seat and the back of the subject than traditional cushions. The results appear to be interesting because, compared with the traditional cushion, there is a reduction of 1.5-2.5 Hz in the natural frequency and the cut-off frequency.

6.1.9.2. Improvements in the Work Station

Appropriate improvements in the work station can only be of minor extent. Amelioration of one of the two stress factors (posture) improves tolerance for the other (vibration). The improvements concern the seat, the controls, and the cockpit.

1. *The Seat*

As a general rule, the contours of the seat should correspond with the comfort angles of Wisner (246). The rudimentary nature of the pilot's seat in certain helicopters must be regretfully noted; the cushion is narrow and does not extend forwards far enough. Shaped side extensions would give better lateral stability to the pelvis. The curve of the seat back should follow the shape of the back, especially in the lumbar region. Sliosberg stresses that the seat back should slope slightly backwards, to avoid the position of forward flexion.

The height of the pilot plays a part and it is, in fact, far from homogeneous. The discomfort of the H34 seat, which was designed for tall American pilots and used by much smaller French pilots illustrates this point (Figs. 187-189).

The seats provide a certain number of adjustments:

- forward and backward

- height adjustment (for example, H21 and Puma seats)

- rake of the seat back.

Access to the controls must be preserved and good visibility ensured. Wisner notes that the multiplicity of adjustments sometimes irritates the user, and it is not certain that the pilot will find the position that best suits his comfort. These costly devices (246) require an anthropometric programme to be undertaken for the study of seats.

In 1965, a prototype seat from the Bretigny Flight Test Centre was studied by Guibal and Broussole (117). It was made from a plastic cushion and seat back filled with polystyrene beads which models itself to the form of the seated subject and is connected to a vacuum source. Once exhausted, the system keeps its shape by means of a non-return valve. This device has the advantage of adapting itself to the requirements of the shape of the subject. The seat, of which much was expected in terms of protection against vibration, was a failure. On the other hand, the impression of comfort given to the pilot, who felt himself to be well supported, was remarkable. This approach has not been pursued.

At present, evacuated cushions filled with polystyrene beads which take up the shape of the pilot are being studied by SNIAS. Installed in the seat of the helicopter, this cushion is adjusted when the pilot is sitting on it. Thus, for each flight, each pilot will have a well fitting cushion.

In our opinion, improvement in the shape of the seat towards well established standards of comfort is now an important factor in the prevention of pain. The skeleton, which gives rigidity to the body, fulfills its function better if it is supported. If the muscles do not have to contract to ensure a good posture of the body, they remain free to play their part as physiological shock absorbers (Figs. 190-191).

Figure 185. Pilot's seat from PUMA SA 330.

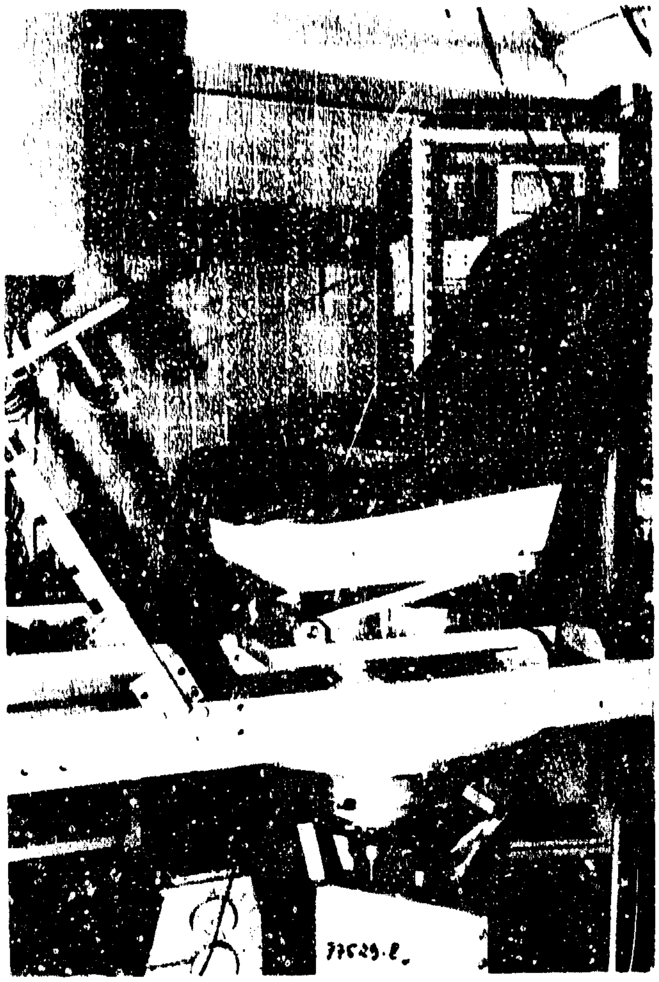


Figure 186. ADOM seat (see text).

2. <u>The Controls and the Cockpit</u>

The advent of standards of comfort should not lead to neglect of the role which a good lay-out of the controls can play.

The problem of the rudder bar now seems to us to have been well resolved. The pedals are generally adjustable to a near or far position, and are so designed that the foot forms a right angle with the leg and the heel rests on the floor.

The cyclic pitch control is also well designed. Its handle should be at a height which allows the right forearm to rest on the thigh. Nevertheless, we note that this control requires the pilot to lean forwards during flight.

The collective pitch control requires the most attention, because it is especially responsible for the peculiar posture of the pilot. The position for minimum pitch, which is practically horizontal in all helicopters, is bad for this reason. It should, in fact, be almost vertical, either by giving the lever an upright configuration or by making it operate as a "floor-mounted throttle".

The lever, which ought to be attached to the floor much further forward at about elbow height, and be accessible without having to lean forwards, should have a much smaller angle of traverse (normally 47°) so that the left elbow does not come into contact with the back of the seat. A hinged support could possibly be attached to the handle so that the wrist and left forearm of the pilot could remain horizontal whatever the angle of pitch selected by the pilot.

This problem of the shape and placement of controls is not one which most manufacturers have much wish to solve. By the same token, the whole technology of controls and piloting should be rethought. The lever is not the only control method available; it was inherited from the technology of fixed wing aircraft, in which it is entrenched. In this context, it is possible to imagine a small console located in place of the cyclic pitch control, with 2 small handles, movement of which would have the same effect as the collective and cyclic pitch controls through an electronic drive system.

While the application of these futuristic and debatable ideas is still awaited, progress is none the less apparent in the introduction of servo-controls, which decrease the forces that must be applied to the controls and allow attenuation of the vibrations that the pilot experiences through them. Similarly, the incorporation of an automatic pilot for certain phases of flight (hovering, cruising) represents a real achievement for the comfort of pilots, who can then relax by releasing the controls.

Finally, it must not be forgotten that visibility from the pilot's position, a real criterion of safety, should be as good as possible, so that the pilot does not have to lean forward. In this respect, mounting the engines at the back of the fuselage far behind the pilot's position permits the construction of advanced glazed or blister cockpits and represents enormous progress compared with helicopters in which the engine is located in front in an enormous nose, like that of the H34. Improvements are also to be expected in the very large instrument panel of heavy helicopters, which is placed between the seats of the pilot and the co-pilot. A reduction in the number of control indicators is perhaps possible, giving pilots and flight engineers only the important instruments; this would lead to a gain of space in the cabin and allow the installation of really comfortable but bulkier and heavier seats, which manufacturers now avoid.

6.1.9.3. <u>Methods Applicable to the Pilot</u>

These are logically concerned with increasing the resistance of the pilot to stress and to avoid overexposing him.

1. <u>Increasing the Spinal Strength of the Pilot</u>

First, it must be remarked that the progress of mechanisation has been a mixed blessing to man. The increasing use of a wide variety of vehicles, such as the automobile, means that man has lost the habit of moving by his own efforts, which has resulted in the development of muscular hypotrophy, in particular of those muscles involved in spinal equilibrium. The helicopter pilot is not exempt from this general proposition; *a fortioti* , the problem will become predominant if his posture at the work station is itself deleterious.

The main concern is thus the reinforcement of the pilot's muscles. He must himself be conscious of this, and it is here that the flight surgeon can play a large part. There is no lack of methods.

Pilots must, therefore, be advised to engage as regularly as possible in all sports which will develop the muscles of the lumbar region and of the back, such as basket ball and volley ball, and especially swimming.

Pilots can be brought together at suitable gymnastic sessions in a sports centre (body building room). Postural and stretching exercises for the spine, and exercises involving the abdominal, gluteal and dorso-lumbar muscles are supervised by an instructor who has followed a special course in spinal gymnastics. This prophylaxis through physical therapy is only practicable if the pilot and his superiors are convinced of its value.

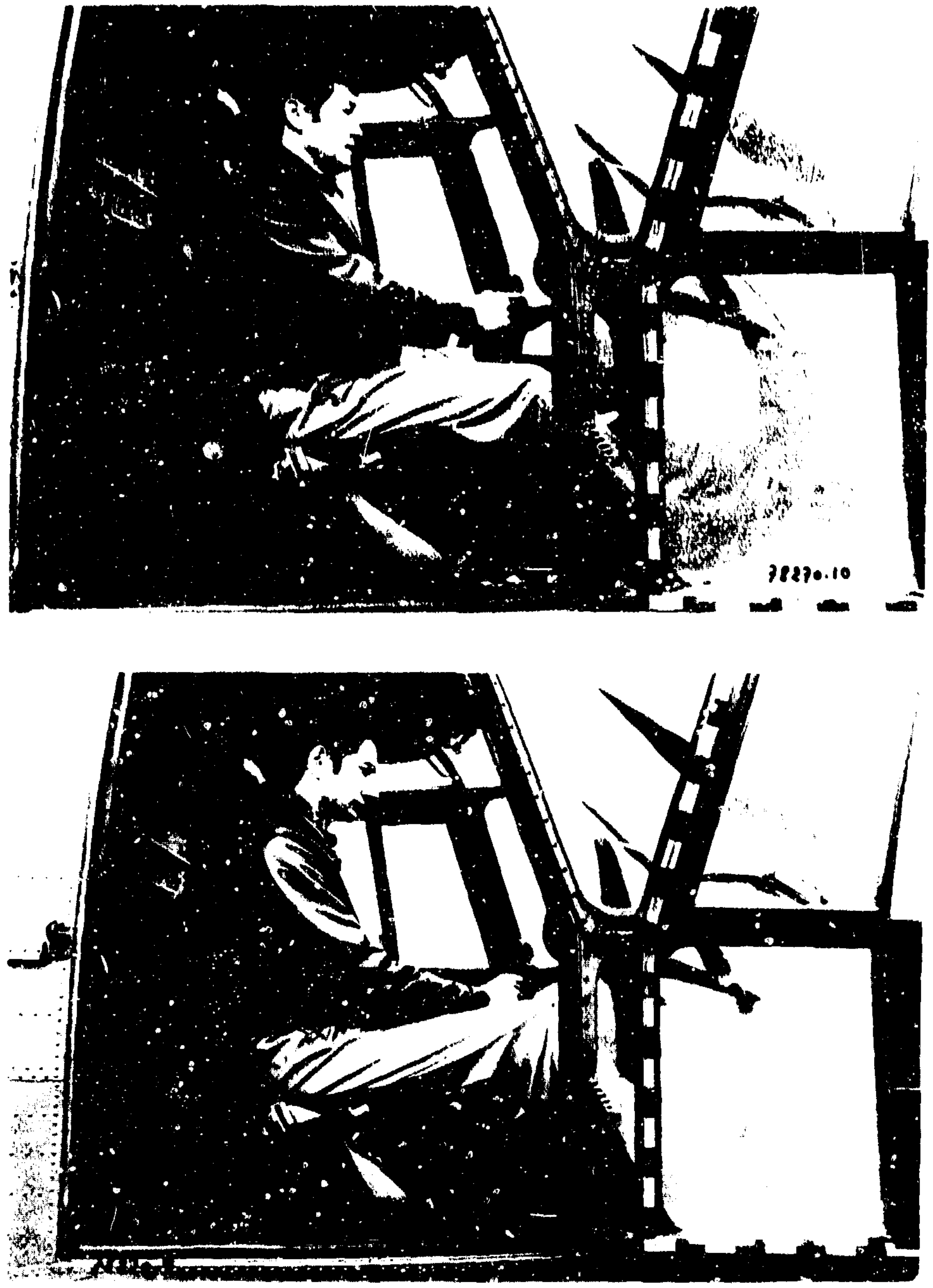


Figure 187. Posture of two pilots of different body build in the pilot's seat of the PUMA SA 330.

Above: pilot of height 1.62 m
poor position of feet

Below: pilot of height 1.88 m
bent forwards
very good position of feet

Figure 188. Posture of two pilots of different body build in the pilot's seat of the Gazelle. Excellent posture of 2 pilots of different stature.

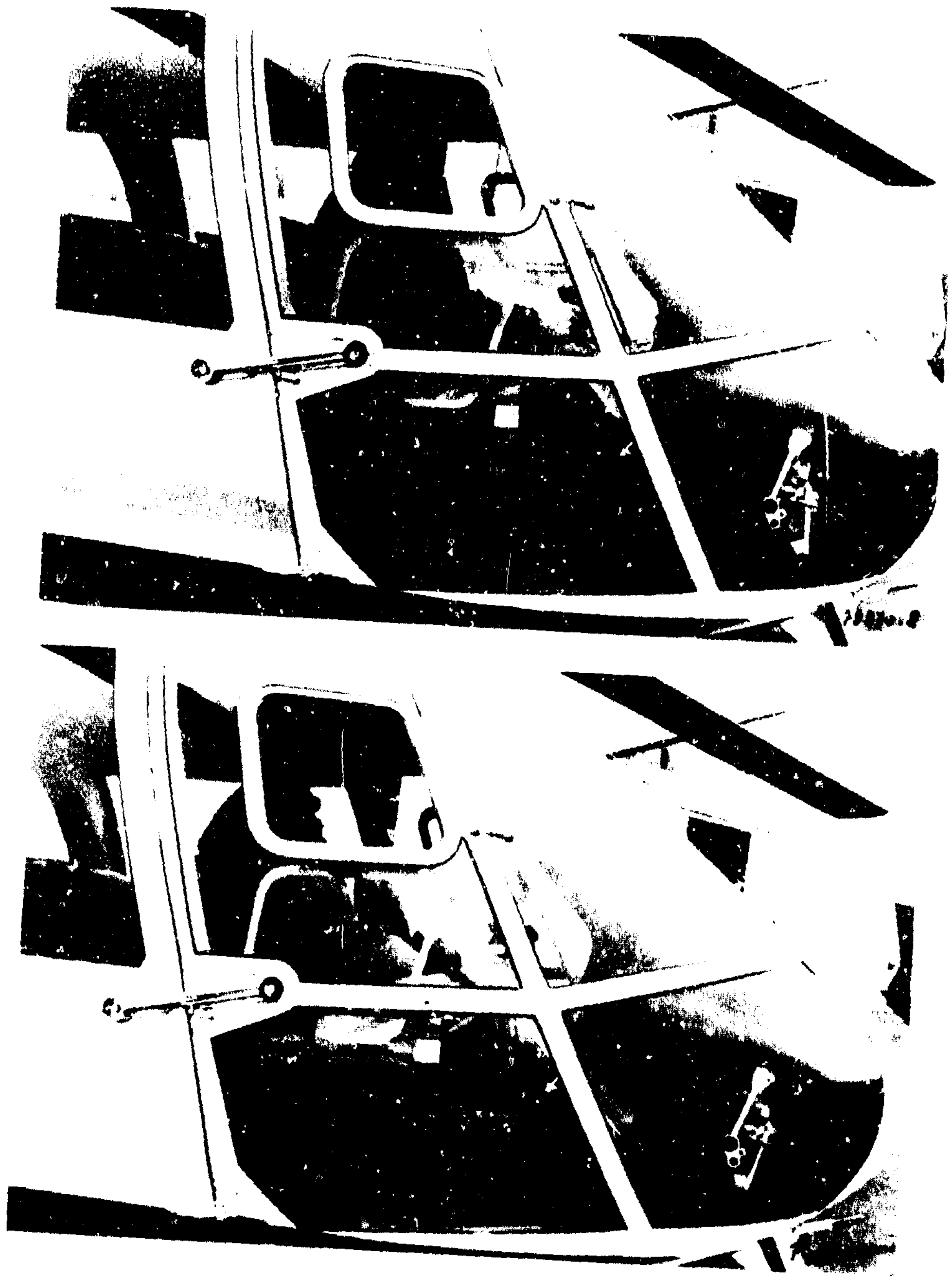


Figure 189. Posture of two pilots of different body build in the pilot's seat of the Dauphin.

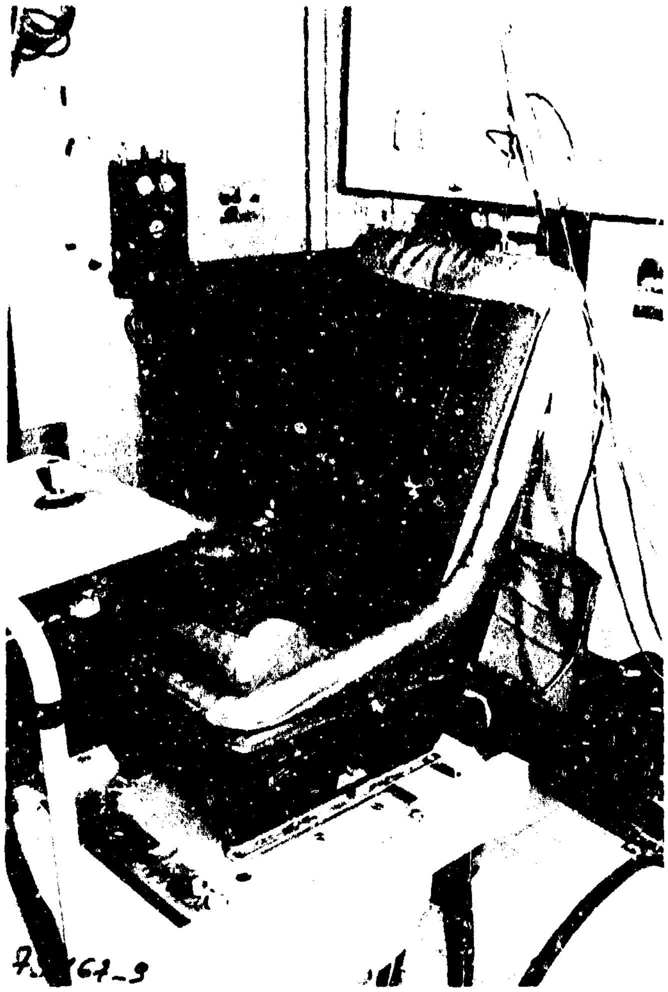


Figure 190. Pilot's seat from Dauphin.

2. Detection of Operational Fatigue

Using an appropriate psychological approach, the flight surgeon must be involved with the problem of detecting the signs of operational fatigue; a pathological state which renders the pilot less efficient, less vigilant and more at risk of an accident. The flight surgeon will also concern himself, in close collaboration with the commander, with the distribution of flight activity.

3. Radiological Fitness Examination

The radiological examination for fitness (see Chapter 7) should be particularly strict, to exclude all conditions that might be aggravated by the stress factors of fight (posture and vibration) (61, 63, 75, 76).

Conclusion

Back pain in helicopter pilots comrises a very interesting clinical entity which persists in spite of the considerable progress in aviation technology (lower vibration level, improvement of the flight conditions). In the years that follow, the flight surgeon should follow the history of these pilots. It must be recognised that these pilots all too often find no understanding of their problems among the experts responsible for giving advice on compensation for the spinal disorder.

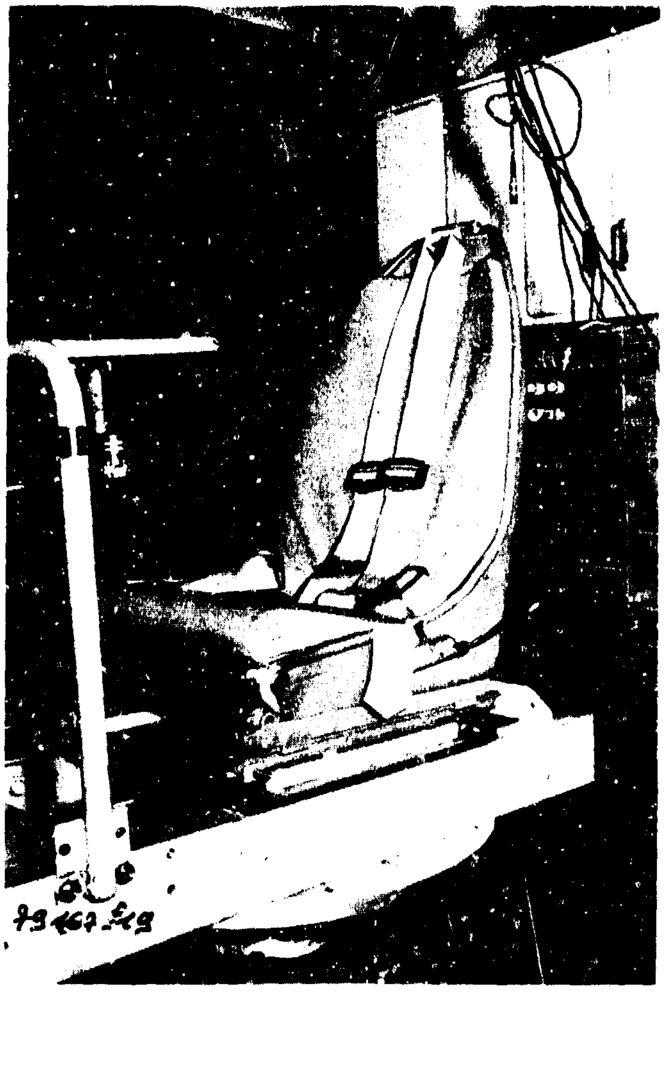


Figure 191. Pilot's seat from Gazelle.

6.2. THE CERVICAL COLUMN OF PILOTS OF COMBAT AIRCRAFT

R.P. Delahaye and R. Auffret

SUMMARY

6.2.1. General Observations

The pilots of high performance figher aircraft sometimes complain of cervical pain during flight at low altitude. The level of vibration is especially high and the pilot is often leaning forward in a fixed position.

Can this be called an occupational disorder? For the last 20 years we have collected together several studies undertaken in various air forces, and it seems necessary to revise viewpoints to take account of changes in the character of the workload, notably in high performance combat aircraft (Mach 2).

6.2.2. Studies of the Cervical Column in Pilots

6.2.2.1. French Air Force (1958-1962)

a. Sais (1958-1962) drew attention to the presence of radiological anomalies in the cervical spine of fighter pilots (subsonic jets). He stressed the influence of the high static and dynamic work to which the cervical column of pilots is exposed. By static (frontal and lateral) and dynamic (lateral) radiological examinations, Sais (199, 200) found 111 normal cases among 228 pilots with a mean age of 25.4 years. The 121 pathological findings (52%) comprised 116 cases of modified lordotic curvature as judged by Arlet's technique (76) (Fig. 195) and 5 cases of arthritis (C2/C3 - one case; C5/C6 - three cases; C6/C7 - one case). The abnormalities of curvature - straightening or reversal - were sometimes associated with vertebral displacement or a limitation of extension. Sais considers that there is a relationship between the abnormal curvature and the flight workload.

b. Delahaye and Edouard (52)

This study, interesting though it was, lacked confirmation from a comparative study of a control group, not exposed to flight stress and with the same age distribution.

Delahaye and Edouard, in an unpublished study, analysed 120 radiographs of the cervical column of fighter pilots (1959-1962). In static examinations, they found more than 60% of abnormal curvatures in subjects aged between 20 and 30 years, while a group of 120 subjects of the same age not exposed to flight stresses and without preceding histories of trauma only exhibited 5% of abnormal curvatures. The authors did not carry out dynamic radiological examinations. However, it was soon apparent that if the buccal plane was not horizontal, changes in the spinal geometry appeared to be present in the lateral views. When the criteria for a satisfactory lateral view were defined, almost the same percentage was found in the two groups.

6.2.2.2. Dutch Air Force (1960)

Botenga, Hamburger and Pfiester (1960) (126, 128), following up the paper by Sais, carried out an important static and dynamic study of lesions of the cervical spine in fighter pilots (National Centre for Aviation Medicine Soesterberg, Netherlands). They examined:

- 100 jet aircraft pilots with an average age of approximately 27.5 years (group A)

- 100 pilots of conventional aircraft with a mean age of 26.1 years (group B)

- 100 student pilots with a mean age of 20.7 years (group C).

All these subjects were apparently in good health without a previous history of vertebral trauma. The technique used consisted of frontal and lateral radiographs in a normal posture, lateral views in maximal hyperextension, and lateral views in maximal hyperflexion.

Hamburger and Pfiester (126) looked for evidence of arthritis and studied anomalies of curvature. They measured the mobility of the cervical spine using their own diagrammatic technique (Fig. 192). The differences found were not significant.

TABLE 6.4

Anomalies of Curvature, Classed as S (Straight), L (Lordotic) and K (Kyphotic)

	GROUP A	GROUP B	GROUP C	TOTAL
S	42	35	26	103
L	51	55	65	171
K	7	10	9	26
Total Examination	100	100	100	300

Mobility of the Cervical Spine

The Dutch authors analysed the of overall mobility of the cervical spine by a statistical method, comparing hyperextension, hyperflexion and total mobility in each of the groups A, B and C.

They concluded that:

- group C (student pilots) had a greater total mobility than either group A or group B, attributable to greater hyperextension;

- group B (conventional aircraft) showed less hyperextension but, on the other hand, more flexion; the total mobility was preserved.

Thus, Hamburger and Pfiester negated the results found by Sais. It should be noted that in the studies by the Dutch authors, the age of the reference population was relatively lower than that of the pilots. They found no difference in the distribution of arthritis.

6.2.2.3. Czech Air Force (1962)

Volek (243) found the rate of arthritis in pilots to be 10% higher than that of a normal population of the same age. He attributed this to the repeated microtrauma of accelerations and sustained vibrations.

6.2.2.4. Swiss Air Force (1962)

Geschwend and Loder (102) published a clinical and radiological study of the vertebral column of 70 military pilots aged between 21 and 46 years, with 233 to 4700 hours of flight experience. They found no clinical or radiological anomaly of the spine in 50.7% of cases and pathology in 49.3%. Among 26 pilots complaining of problems with the neck or the shoulders, they found only 8 with a normal curvature of the cervical spine.

6.2.2.5. French Air Force (1967-1979)

In the face of these different radiological studies, we asked ourselves the following question. Must abnormal curvatures or arthritic signs in the cervical spine of pilots be attributed to their occupation? Long term studies were involved, requiring detailed knowledge of the variations in the normal radiological anatomy of the spine as discovered in recent years. At the same time, comparison with a control group, and a rigorous statistical study, were essential.

1. Gueffier and Delahaye (54, 55, 115) studies the results of dynamic radiological examinations of the spine in 103 aircrew, compared statistically with a normal reference population.

From this preliminary work, which used the measurement technique described by Hamburger and Pfiester (126), they tentatively concluded that some findings are more frequent in flying personnel; abnormalities of curvature, straightening, arthritis. However, these studies must be extended.

2. Later, in 1972 and in 1976, we followed the same protocol each time in comparing 100 pilots from fighter squadrons with a group of 100 control subjects of the same age. This work, extending over 8 years, has not shown a detectable difference between the pilot group and the control group.

Conclusion

Studies over an extended time are needed to continue this appraisal of the cervical spine in pilots of combat aircraft; especially the new combat aircraft now being brought into service, in which accelerations of high amplitude are more frequent. For the moment it is not possible to state with certainty that flight in high speed combat aircraft contributes to the development of cervical arthritis.

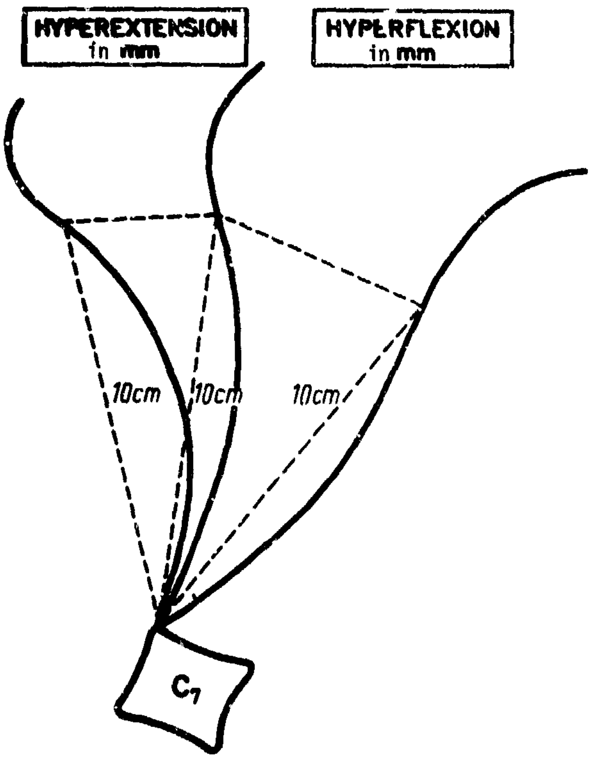


Figure 192. Study of the mobility of the cervical spine (from Hamburger and Puister, 126).

CHAPTER 7 - THE SPINE AND FITNESS FOR FLIGHT

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P. Doury, P.J. Metges and C. Kleitz

SUMMARY

The study of the harmful effects of flight factors and the analysis of different sets of statistics confirm that the vertebral column is subjected to a certain number of more or less severe stresses in the course of a flying career. It seems necessary to define some criteria of fitness, as far as the spine is concerned, in relation to the type of aircraft.

These conditions for fitness are considered from two very distinct aspects:

- fitness at the time of admission of flying personnel

- fitness upon re-examination and after air accidents.

7.1. ON ADMISSION

7.1.1. Clinical Examination

This examination should meet the requirements defined in paragraph 5.4 and place particular stress upon the balance of the spinal musculature, and on the clinical detection of scoliosis, accentuated kyphosis and inequalities in the length of the lower limbs.

7.1.2. Radiological Assessment of Fitness

7.1.2.1. Aim of Examination

At present, all candidates for flying duties in the French Air Force undergo a mandatory radiological examination of the entire spine. This reference dossier has a triple purpose (18, 48, 52, 76):

1. The exclusion of serious lesions likely to alter the strength of the spine, and incompatible with flying duties.

2. The study of occupational pathology.

3. Subsequent comparison with an examination carried out after trauma (ejection, air accident). In this context, it is necessary to emphasise the importance of specifying long retention times for the records in centres of aviation medicine, so that such comparisons can actually be made 10 or even 15 years after the preliminary examination.

Most experts in other European air forces recognise the importance of this examination (14, 18, 249, 250). However, some organisations (RAF, USAF) consider that radiological examination of the spine should not be mandatory, for the following reasons (9):

- increase in the radiation dosage to flying personnel

- absence of a significant bearing on the flying future of the candidates.

This position does not seem logical to us:

- there are numerous acquired disorders or congenital anomalies without clinical manifestations which can reduce the strength of the vertebrae and alter the distribution in the spine of inertial forces occurring in some accidents (ejections, in particular);

- the absence of a reference dossier, which is always useful to safeguard the medico-legal interests of the state and of the pilots, should be emphasised

- if systematic initial radiological examination is not carried out, it seems to be impossible to undertake serious scientific studies of the occupational pathology of flying personnel, and of the aging of the spine. Moreover, we would not have been able to describe, in various studies, the development of the normal radiological features of the vertebral column in the young, or to stress the need for a change of attitude to these variations by the experts (56, 58)

- the radiation to which flying personnel are exposed at the admission examination remains low. In the present state of scientific knowledge, it is probable that it does not constitute a radiobiological danger. In practice, account must be taken of the balance between advantage and disadvantage; and the advantages to be gained from the radiological examination are indisputable. This conviction, which is based on more than 20 years experience of health care and of evaluation of French military and civil flying personnel, has not been unanimously accepted. In the different countries of NATO, there is no common view on the advisability of conducting systematic radiological examination of the spine at the time of acceptance (see Table 7.1 (9)).

TABLE 7.1

	Routine Radiological Examination	Remarks
USAF	No	Carried out if there is a previous history, or clinical indications.
US Army	Yes (?)	For detection of spondylolysis or spondylolisthesis, or clinical indications.
French Air Force	Yes	Whole spine, on admission only.
German Air Force	Yes	Whole spine, on admission and 5 years later.
Hellenic Air Force	Yes	Thoracic and lumbar spine.
Italian Air Force	Yes	Whole spine.
Royal Air Force	No	

7.1.2.2. Technique Used

The entire spine is examined from two aspects: frontal and lateral. Two techniques are used:

- radiograms of the whole spine
- localised radiograms.

a. Radiograms of the Whole Spine (9, 19, 116, 285)

The technique of "pan-radiography" employs two films, 30 x 90 cm, with graded intensifying screens to compensate for the differences in density between the cervical, thoracic and lumbar segments. This technique is the most widely used, but it is possible to obtain identical results by placing a movable filter in front of the X-ray window, at the cost of a modest increase in the radiation dosage. Two negatives (frontal and lateral) are taken of a standing, barefoot subject with a tube to film distance of 3 metres. The field of view of the radiograms includes the lower part of the skull, the spine and the entire pelvis. Posture can be determined. This method usually suffices for the compilation of the reference dossier, but the need to employ segmental techniques for the fine study of the vertebral structure in corpulent subjects must be noted.

b. Localised Radiograms (52, 76)

The radiographic examination includes a minimum of 8 negatives:

1. A lumbar/pelvic/femoral negative (frontal view) with the feet rotated inwards through 20°. It includes the tops of the acetabula and is made in the posterio-anterior direction (288).

2. A lateral negative of the lumbar spine.

3. A frontal view centred on the L5/S1 disc. The angle of the beam should take account of the slope of the disc, as assessed from the lateral negative.

4 & 5. Frontal and lateral radiograms of the thoracic column (287). For the lateral view, the subject folds arms high in front of him (elbows touching, forearms in front of the face). He should not adopt the posture of a water-skier, so as not to produce an exaggeration of the physiological thoracic kyphosis.

6 & 7. Frontal views of the cervical column.

8. A radiogram of the atlas and axis, taken with the mouth open.

It should be noted that the last exposure is made in addition to two pan radiograms (frontal and lateral).

Supplementary Examinations

Supplementary negatives are made as required. Radiograms with the subject lying down permit the assessment of possible reduction in a scoliotic posture detected on the standing negative.

Localised exposures from various aspects (frontal, lateral and sometimes oblique), and frontal and sagittal tomograms are necessary for the evaluation of congenital malformations.

Dynamic negatives explore functional locks or examine lateral nipping of the discs. Techniques requiring the use of contrast media (radiculography, myelograms) are not used in the initial medical examination of flying personnel, or in monitoring studies.

The examination of the X-rays by the radiologist allow him to define a standard index of fitness. He must always take into account the muscular build of the subject and the results of the clinical examination.

7.1.3. Static Disorders of the Spine

These abnormalities are found both in the frontal plane (visible in the antero-posterior view) and the sagittal (lateral) plane.

7.1.3.1. Static Disorders in the Frontal Plane

Alterations of the spinal posture occur in the thoracic and in the lumbar columns. For many years, the definition of normality has been based on the following principle: a vertical line drawn between the external occipital protuberance and passing through the spinous processes ends at the tip of the coccyx. However, the conditions under which the radiograms are made (vertical stance) and perhaps a revision of the radiological criteria of normality have profoundly modified this point of view. Only 25% of subjects examined in the standing position conformed to the old definition of normality (Delahaye et al, 56, 58, 76, 289-291).

A new definition of normal posture must accordingly be accepted, which takes account of data obtained from a detailed inventory of the spines of 3,500 young adults (289-291). We have set a limit of 10° on the angle of scoliosis coming into this category of "expanded" normality (56, 58, 60, 173). Two types of modification to the vertebral posture in the frontal plane may be described:

- the scoliotic posture

- true scoliosis.

1. The scoliotic posture (Fig. 193) gives rise to one or more curvatures of the spine. It is often secondary to inequality in the length of the legs, revealed in the frontal view by the presence of a pelvic tilt.

The scoliotic posture, like true scoliosis, may be associated with an angulation of the upper surface of the sacrum to the horizontal, with an asymmetry of the body of L5. This scoliotic posture appears in frontal views as an inflection in the line of the spinous processes. Two important features should be looked for:

- absence of rotation of the vertebral bodies

- reduction of the specific disorder on lying down.

2. True scoliosis is the more common variety and consists of two main types:

- common "minor" scoliosis, which is generally benign

- more severe scoliotic disease.

a. Common minor scoliosis develops in infancy and takes the form of abnormal spinal curvatures with rotation of the vertebral bodies. It usually leads to a painful kyphosis.

The limits of each curve are defined by the "neutral" vertebrae. These are the vertebrae most inclined to the horizontal, whose spinous processes are reasonably well centred on the projection of the body. The uppermost vertebra has the greatest inclination, and the largest degree of rotation. Its spinous process projects inside the concavity of the scoliotic curve. Any case of scoliosis should be measured, and we use the method of Cobb to calculate the scoliotic angle (Fig. 194).

The line of the top surface of the upper neutral vertebra and that of the bottom surface of the lower neutral vertebra are drawn and extended. By construction, the angle formed by the two perpendiculars to these lines defines the scoliotic angle of the curvature under consideration.

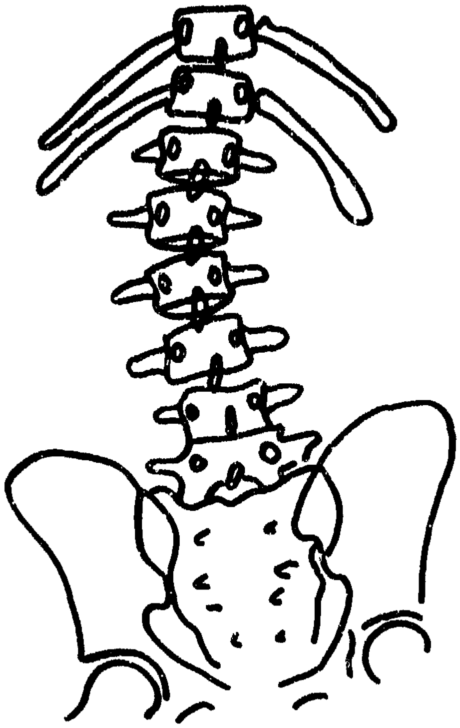

Figure 193. Lumbar scoliotic posture resulting from pelvic imbalance. No rotation of the vertebral bodies; reducible by splinting or by lying flat.

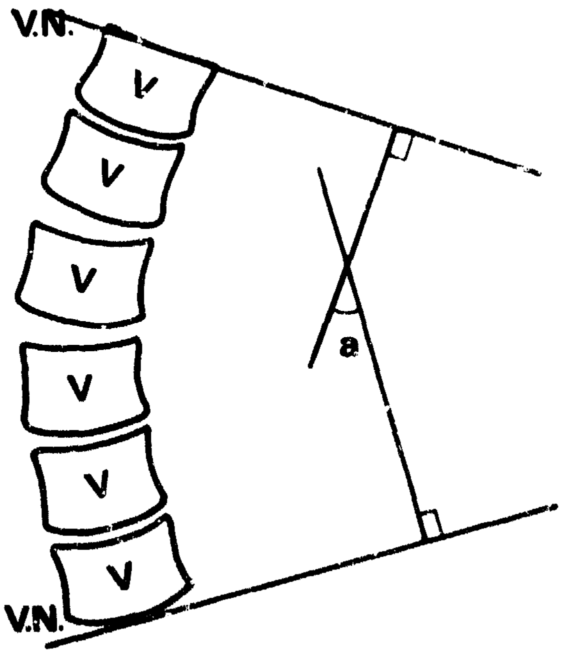

Figure 194. Measurement of the scoliotic angle (after Cobb). VN = Neutral Vertebra

To reduce the error of measurement, the use of tracing paper and a fine pencil are recommended. It is useful to examine the iliac crests and to investigate their union (Risser's test), which allows the arrest of development of the scoliosis to be confirmed. We repeat the need to look for an inequality in the length of the two legs which, as for the scoliotic posture, produces tilting of the pelvis, asymmetry of the body of L5 and obliquity of the upper surface of the sacrum.

b. Scoliotic disease continues to develop until the end of the growth period. The scoliotic angle is often large. Subjects with this type of scoliosis are always unfit for national service and, *a fortiori*, for employment as military aircrew.

3. Scoliosis of Known Origin

Radiograms reveal the presence of major congenital abnormalities: supernumerary hemi-body, supernumerary hemi-vertebra (most common), hypoplasia or aplasia (more rare). The angle of the scoliosis, often large (more than 40-50^o), exceptionally has values between 10^o and 20^o. In any case, the presence of major anomalies forces a decision of unfitness to be made.

7.1.3.2. Static Disorders in the Sagittal Plane

In the sagittal plane, the spine exhibits 3 successive curves, which can be analysed in lateral negatives and which result from the adaptation of man to the upright posture. The curves increase the strength of the spine. They depend upon various factors many of which lie outside the bone (ligamentary and muscular factors). Normality is judged on the criterion that a plumb line dropped from the external auditory meatus should pass through the middle of the disc of L5/S1 and opposite the greater trochanter. Thus, each stage (cervical, thoracic, lumbar) has a certain degree of curvature which should be measured for the estimation and possible quantification of the static disturbance.

1. Cervical Lordosis

We use the method described by Arlet (Fig. 195). A straight line is drawn tangential to the posterior border of the odontoid process, meeting the posterior inferior angle of C7. The deflection of the lordosis is the length of the perpendicular measured from the posterior and inferior angle of C4. This measure is only of value if it is made on a truly lateral negative (horizontal occipito-mandibular plane). It is useful to specify the lordosis by the ratio C/F where C, expressed in cemtimetres, measures the chord. F (in millimetres) represents the depth of the lordosis. Normally, this ratio is about 1. Hyperlordosis is indicated by values less than 0.8. The normal cervical spine is characterised by a considerable degree of flexibility. In rare instances, a disturbance of cervical posture is a factor in the assessment of fitness for flight.

2. Thoracic Kyphosis

This is determined by the angle at its centre (287). This angle is measured from the intersection of a straight line parallel to the lower face of D11 with one parallel to the superior facet of D4 (Fig. 196). These two lines meet in front to form an acute angle. D4 and D11 are the chosen reference vertebrae because those at the extremes are very often masked on the radiograms. In practice, the angle at the centre is most easily measured by drawing the perpendiculars to two straight parallel lines, one at the lower face of D11, the other at the upper surface of D4.

This measurement can only be made if the radiogram was taken under technically perfect conditions. In particular, it should be remembered that the "water-skiing" posture, which accentuates the physiological thoracic kyphosis, must always be avoided. The central angle varies from 30-35^o in a normal subject.

3. Lumbar Lordosis (76, 288, 291)

In the lumbar spine, it is very difficult to obtain an index of normality by mathematical measurements. Accordingly, numerous other indices have been proposed. For several years, we have systematically carried out a great number of measurements on the lumbar column, an exercise made easy by the use of data processing. We reported the results of this rather disappointing study in 1973 (291).

No single measure defines lordosis and it is therefore necessary to use several readily reproducible numerical indices (288, 291).

1. The sacro-vertebral angle, formed by the tangents to the anterior face of L5 and the anterior face of S1 (Fig. 197). The normal value is 129^o; 95% of determinations lie between 110^o and 147^o.

2. The inclination of the upper surface of the sacrum to the horizontal is, on average, 30^o (Fig. 198).

3. The depth of lordosis is independent of the position of the sacrum. The chord of the lordosis joins the posterior upper corner of L1 to the posterior upper corner of S1. The depth of this arc is measured at L3. Its mean value is 19 mm, with a standard deviation of 6 mm (Fig. 197).

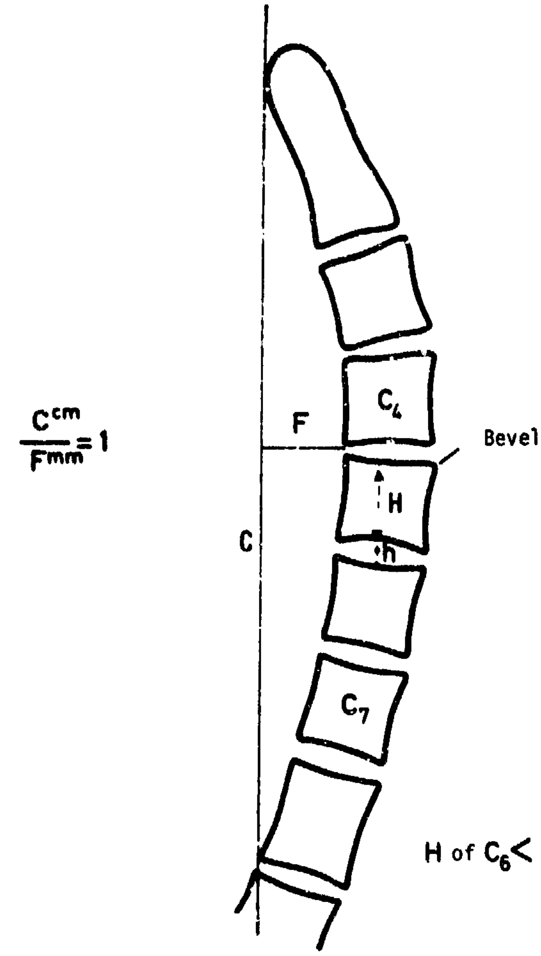

Figure 195. Measurement of cervical lordosis (from Arlet).

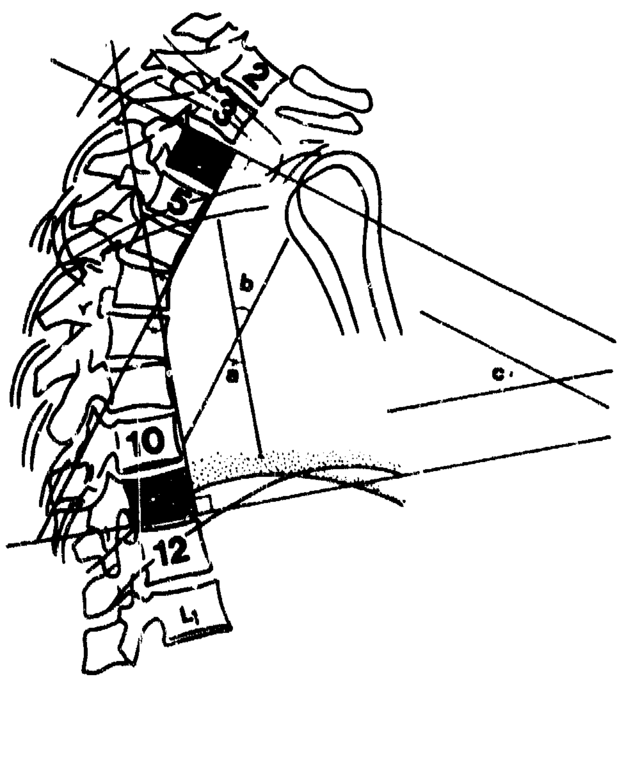

Figure 196. Measurement of thoracic kyphosis.
Normal value 30-35°

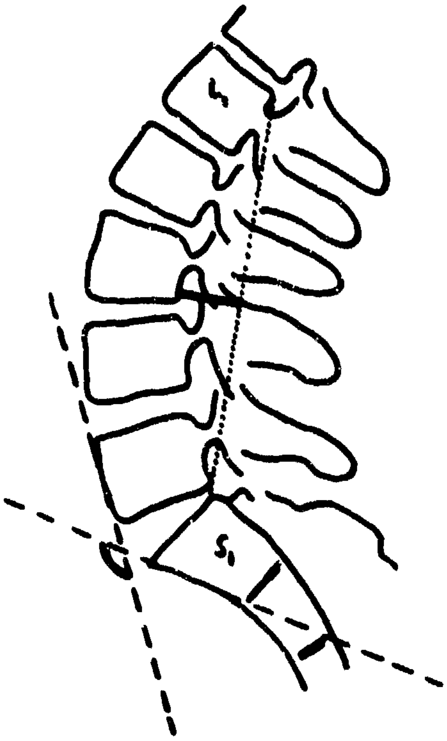

Figure 197. Sacrovertebral angle and depth of lordosis.

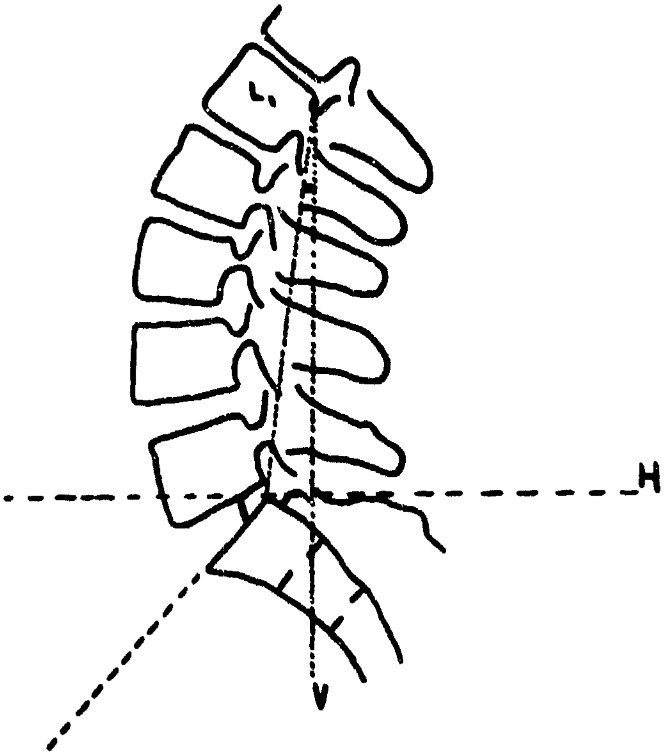

Figure 198. Inclination to the horizontal of the sacral plateau and index of reversion.

4. The index of inversion (288, 291) takes account of:

. the vertical dropped from the posterior superior angle of the body of L1

. the horizontal passing through the posterior superior angle of the body of S1.

The index of inversion is measured either by (Fig. 198):

. the distance which separates the posterior-superior angle of the body of S1 from the intersection of the vertical from the posterior superior angle of L1 to the horizontal passing through the posterior superior angle of S1

. the angle formed by the lumbar chord with the vertical line defined above, passing through the posterior superior edge of L1.

The average angle of the inversion index is 6^{o} 30', with a standard deviation of 9^{o}, which indicates a very large dispersion around the mean.

The multiplicity of measures from the sagittal plane illustrates the difficulty of numerical specification of the lumbar geometry (288-291).

7.1.4. <u>The Sequelae of Vertebral Osteochondrosis (Scheuermann's Disease)</u> (76, 203, 319)

Scheuermann's disease is an osteonecrosis of the vertebral epiphysis which develops during growth. The sequelae appear after the fusion of the epiphysis (16-18 years of age).

Because of the high incidence of these after-effects and their extreme polymorphism the attitudes of experts to their significance for the assessment of fitness have not always been unanimous. Within the context of this book, we have thought it appropriate to review some of the statistical data and to describe the radiological signs carefully. This course seems to us to be all the more legitimate because the syndromes of after-effects of vertebral osteochondrosis are rarely studied or described in detail in medical reports.

7.1.4.1. <u>Incidence</u>

We have amassed two sets of statistics (Table 7.2). The complete results of these two statistical studies appear in the appendix on pages 283 - 286. The incidence appears to have been constant since 1969 (12% of the population studied). It is markedly less than that observed in Sweden (25-30%) and in the USA (25%).

TABLE 7.2

	PLACE	POPULATION	% OF SEQUELAE
I	CPEMPN, Paris Mangin, Gueffier, Metges and Delahaye	2500 military aircrew candidates (average age 19-23 years)	12.08
II	HIA Begin, St Mande Delahaye, Metges and Kleitz (1971-78)	2500 military personnel	12.75

7.1.4.2. <u>Fundamental Radiological Signs</u>

These consist of postural disturbances of the spine and morphological anomalies of the vertebral bodies and the interfaces (319).

1. Postural anomalies are often present but are not constant. They comprise hyperkyphosis and scoliosis.

Lower thoracic hyperkyphosis (angle greater than 35^{o}) was the postural disorder most often encountered in the personnel surveyed (55% of cases). This hyperkyphosis is centred on D8 and D9 and is always associated with a predominance of lesions at this level of the spine.

The type of scoliosis most frequently seen has an angle of less than 20^{o}. Kyphoscoliosis is quite frequent (30%).

2. Morphological anomalies of the vertebral bodies and interfaces. The following table summarises the major radiological signs visible in the spine.

Abnormalities of the end plates
Discontinuities of the nucleus
Nuclear indentation
Intraspongiosa hernia
Anterior retromarginal hernia
Abnormalities of the marginal epiphysis
Deformation of the vertebral body
Changes to the interface
Vertebral locks

Abnormalities of the End Plates

A laminated appearance of the end plates affects mainly the lower plateau and the upper one more rarely. These lesions, which are best seen on the lateral view, lie in the region of the hyperkyphosis (D8/D9). According to the case, the end plates may be thickened, laminated into successive layers, undulating, fluted, shredded or crenellated. Their outlines, although irregular, are not blurred but often consolidated. Quite frequently, two adjacent wrinkled surfaces, separated by an attenuated disc, appear to match each other in contour (the so called Puzzle sign). Slightly irregular end plates could be discerned in 74% of the cases observed in our two sets of statistics of sequelae of Scheuermann's disease. Gross irregularities were present in 15%, and in 10% of cases the end plates were regular.

Discontinuities of the Nucleus

These comprise nuclear indentation, intraspongiosa hernias and anterior retromarginal hernias.

- Nuclear indentation appears as a notch with a large radius of curvature in the posterior half of the vertebral end plate. It is usually outlined by a more or less thick band of consolidation. Lesions to two adjacent end plates give the disc a biconvex appearance. This isolated lesion is very frequently encountered, and it seems that it should not be considered pathological.

- Intraspongiosa hernia (Schmorl's nodule) appears mainly in the lower vertebral end plate, preferentially between D7 and L1 (almost always in the region of hyperkyphosis). Most often in the mid-line, but less commonly paramedian, the Schmorl nodule has the form of an open semicircular dish 5 mm deep and 20 mm wide, which approaches the vertebral end plate in a gentle curve. The distinct edges are surrounded by a rim of condensation.

In profile, this depression is located primarily at the junction of the middle and posterior thirds of the surface, especially in the thoracic region of very advanced cases with severe sequelae (wedge compression in particular). An association with a laminated appearance of the end plates is not uncommon.

- Anterior retromarginal hernia occurs predominantly at lumbar level, and almost always on the upper end plate of the vertebra.

In a lateral view, it is seen classically as a notch behind the anterior margin, with a gentle slone to the rear, but with a usually vertical front face.

More rarely it appears in a symmetrical form. It is sometimes accompanied by a general reduction in the height of the intervertebral disc. Sometimes an osteophytic excresence is seen in front of the vertebral border.

This anterior retromarginal hernia, which is a variety of the intraspongiosa hernia, is often of great size. It is most frequently associated with other signs of sequelae of Scheuermann's disease, but it may also appear in isolation.

Abnormalities of the Marginal Epiphysis

These consist essentially of an absence of fusion of the vertebral corners. English authors refer to the condition as "free epiphysis" or "paradiscal defect". It frequently occurs at the anterior superior corner of the vertebral body, and more rarely at the lower corner. On a lateral X-ray, it appears as a wide clear line located at the site of implantation of one or more angles. This detached anterior corner rarely fits the contours of the vertebral body. It is either small, atrophied or even punctate, or large as a result of excessive growth, when it overlaps the vertebral contours. We consider that this

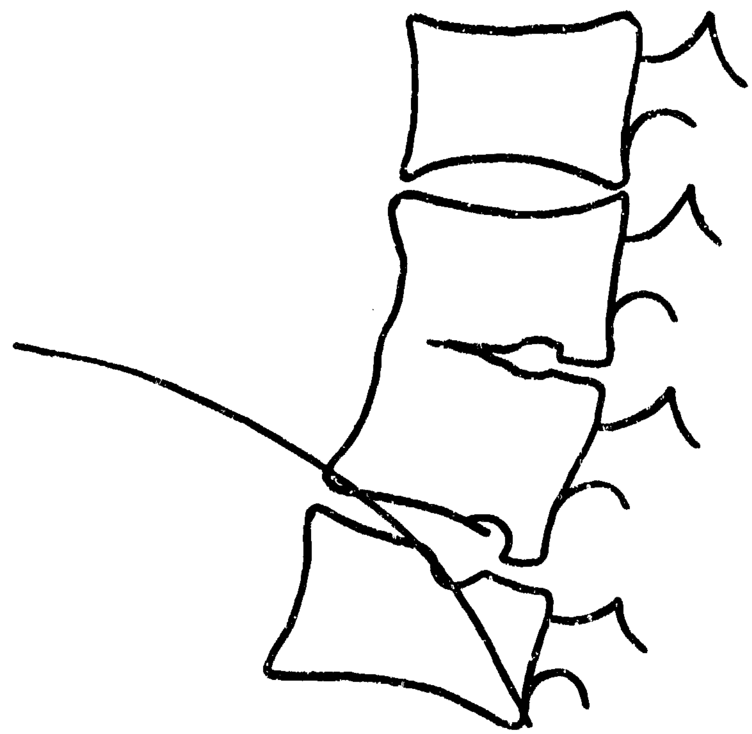

Figure 199. D10-D11 lock, secondary to Scheuermann's disease.

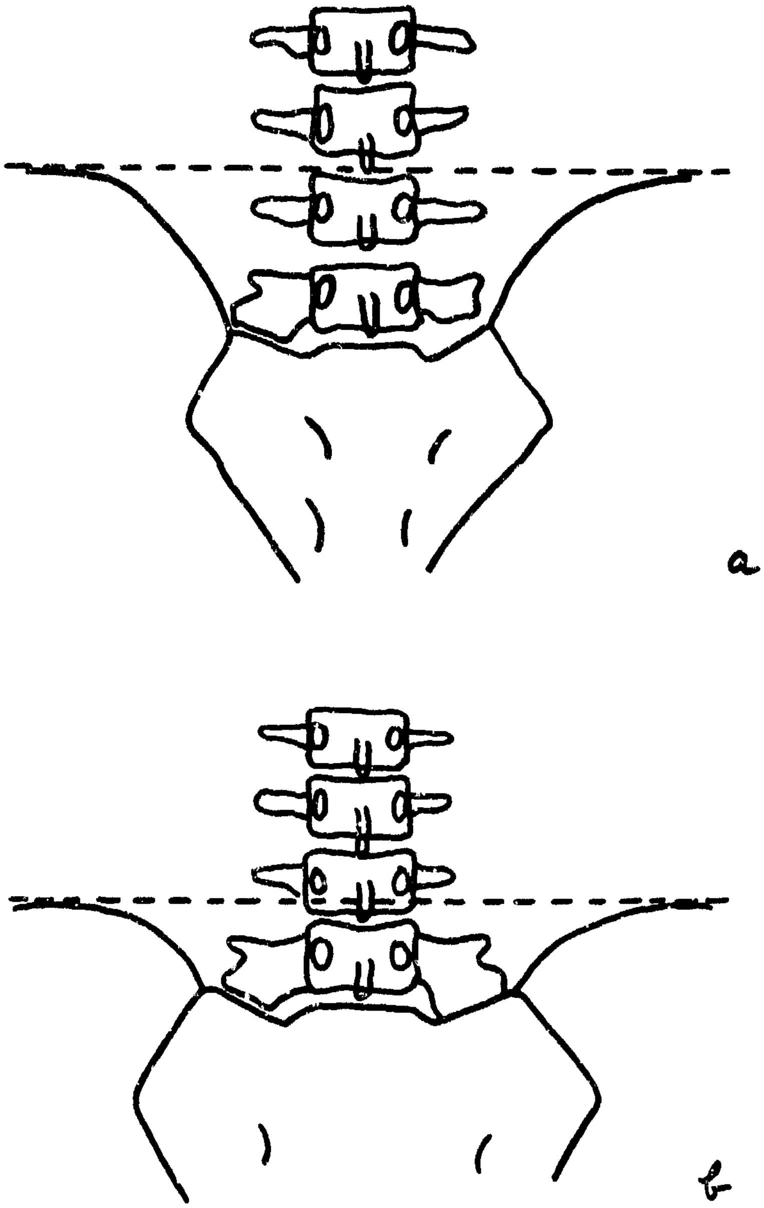

Figure 200. a) Lumbo-sacral transtional anomaly with an ambiguous vertebra of which the right transverse process is hypertrophied and forms a new joint, without disengagement of the junctional vertebra.

b) Marked disengagement of the junctional vertebra above the line of the iliac crests.

picture is not specific to the sequelae of Scheuermann's disease.

Deformation of the Vertebral Body

There is frequently a reduction in height of the anterior part of the vertebral body. In some cases the deformation is minimal, but the upper and lower end plates of the vertebra are not parallel. They slope gently forwards. There are numerous variants of this picture, ranging from a trapezoidal shape to a moderate collapse if the height of the entire vertebral body is reduced. Most frequently, the deformation is at the expense of the anterior part of the vertebral body, with a relatively regular slope from back to front. At the anterior corner this deformation generally involves several vertebrae and is predominantly in the middle region of a scoliosis. Anteroposterior elongation of the vertebral body is frequently observed, in association with collapse and with intraspongiosa hernia. This appearance corresponds to an anomaly in the sagittal development of a vertebral body. According to Knuttson it is pathognomonic of Scheuermann's disease.

Change to the Vertebral Interface

This consists of total or partial constriction, predominantly in the anterior part, related to lesions of the vertebral end plates. It is almost invariable when the disease is in the thoracic region.

Vertebral Lock (76, 301, 319) (Fig. 199)

In about 5% of cases, this condition gradually develops towards the age of 15 years. Fusion occurs between two vertebral end plates brought into contact by a massive prolapse of the anterior part of the disc. The elective site for these locks is the lower thoracic region (D9-D11), corresponding with the predominance of the lesions of Scheuermann's disease in this region. The lock has the radiological characteristics of an acquired lock. Its presence modifies the distribution of inertial forces. In association with other manifestations of the disease, this condition constitutes grounds for unfitness. The less common lumbar sites are quite often associated with a straight lumbar spine. They are characterised by the presence of large anterior retromarginal hernias on the superior end plates.

7.1.4.3. Relationship Between the Sequelae of Scheuermann's Disease and Trauma

This has been little studied (319).

The very frequent presence of hyperkyphosis among the sequelae favours the development of fractures by hyperflexion; the traumatic lesions appearing generally at very high levels (D2-D5), and sparing the zones most frequently affected by Scheuermann's disease (D7-D10). These observations have been made in pilots after ejection who, by the regulations then in force, were accepted as flying personnel without a radiological examination carried out on admission. It must be recognised that the significance and effect of these sequelae, which can lead to arthritis are difficult to judge at the preliminary medical examination, but experience has shown that subjects with the condition, especially in the lumbar region, are more often affected by lumbar pains when flying helicopters.

7.1.4.4. Classification of Sequelae

We have recently proposed a classification into slight, moderate and severe.

a. Slight - minor irregularities of the end plate with lamination and Schmorl's nodules without change to the general morphology of the vertebrae.

b. Moderate - wedge deformation of a vertebra, either isolated or associated with other signs, most particularly with localised notching and nipped discs.

c. Severe - anterior wedge deformation of more than one vertebra, associated with irregularities of the end plates, Schmorl's nodules, and lamination affecting other vertebrae, with severe disturbance of the sagittal geometry (hyperkyphosis).

7.1.5. Congenital Anomalies of the Spine

Common and varied, such malformations create everyday difficulties in the interpretation of spinal radiograms. Above all, account must be taken of the effect of these anomalies on the strength of the spine and of their later development in the course of a professional life the duration of which may be 24-30 years (52, 58, 60, 61, 62, 73, 76, 292, 307, 331, 416).

7.1.5.1. Splitting of the Spinous Processes

This is a common anomaly (about 20% of the population) which occurs preferentially at the level of S1, then L5, and more rarely at C5, C6, C7 and D1. This anomaly appears in the frontal view as a linear translucency of variable breadth, most often in the midline. It is accepted that it does not diminish the strength of the spine and it must be considered as a simple congenital variant without pathological significance. In all cases it consists of a simple splitting of the posterior arch; still improperly called spina bifida occulta. This expression should be removed from the medical vocabulary, because it

suggests the severe meningospinal dystrophy which comprises true spina bifida, combining major splitting of the posterior arch and meningomyelocele.

7.1.5.2. Transitional Anomaly of the Lumbosacral Junction (61, 62, 292)

This is relatively common (nearly 10% of the population) and is due to a defect, or conversely to an exaggeration, of the process of differentiation of the sacrum. Its contribution to the appearance of lumbar or sciatic pain is suspect; in some series, 30-50% of patients with herniated discs have such anomalies of the lumbosacral junction.

Two varieties are usually described; sacralisation of L5 and lumbarisation of S1. In practice, this differentiation is not always easy, and may be impossible if there are other transitional anomalies at D12 and L1. In any case, the precise definition of the ambiguous vertebra is devoid of interest. It is enough to look for the differentiation of a new intervertebral joint, and the existence of one or two new sacral transverse articulations (Fig. 200).

It will be recalled that L5 is normally embedded between the wings of the ilium. In case of disengagement, the pivot vertebra occupies a high position, partially or totally above the line joining the two iliac crests. It is only connected to the crests from a distance by long, thin, weak, oblique ligaments which are incapable of exerting the least restraint on its mobility. At the junction of this mobile component and a fixed part, the intervening disc is exposed to a true functional overload, predisposing to the early development of lesions from wear and degeneration (herniated disc, arthritis).

In order to clarify the situation, projection of the lower margin of the transverse processes of the new junctional vertebra above the line joining the crests may be called marked disengagement. In moderate disengagements the lower margin of the processes lies below the inter-crestal line.

The new joints are usually transverse sacral. They rapidly become the site of arthritic changes. Finally, this type of malformation may be asymmetrical, with significant effects upon the geometry immediately above it.

7.1.5.3. Spondylolysis and Spondylolisthesis (62, 292)

Spondylolysis is a break in continuity of the posterior vertebral arch with separation of the pedicles. Unilateral or bilateral, it affects the fifth lumbar vertebra in the vast majority of cases, and more rarely L4 and L3.

In isolation, it causes no clinical manifestations and is easily recognised on frontal, lateral and three-quarter view radiograms (Fig. 201) as a clear line dividing the isthmus and separating the pedicles.

Spondylolisthesis is a condition characterised by the sliding forwards of a vertebral body (most often L5) on the subjacent vertebra (the sacrum). Present in nearly 3% of the population, the displacement generally appears before the twentieth year of age (between 8 and 15 years). Various forms of pain are its usual clinical manifestation. The lateral X-ray is the most revealing (Fig. 202) showing that the displacement evolves in three stages, each corresponding to one third of the underlying vertebra.

This view also allows the assessment of enlargement of the intervertebral foramina, possible deformation of the body of L5 and of the sacrum, the state of the disc, and the presence of secondary osteophytes. Spondylolisthesis is, in fact, an anomaly that seriously disturbs the normal spinal geometry. The slipping of the body of L5 leads to overloading and deterioration of the disc of L5/S1 and of the upper end plate of S1 when weights are lifted in an incorrect manner, and hence to arthritis and to deformation of the sacral shelf (282).

7.1.5.4. Congenital Locking (52, 62, 292, 416)

This common malformation results from the partial fusion of one or more vertebrae. A congenital lock must be differentiated from a total or partial acquired lock (anterior or posterior). This type is characterised by a disc remnant, by preservation of the normal height of the vertebral bodies, by the straight line forming the posterior contour, and by diminution in the vertical extent of the intervertebral foramina. C2 and C3 are the vertebrae most often fused (1.04% of our series of 2500 aircrew candidates).

Congenital locks do not alter the strength of the spine. Their presence should lead to a decision of unfitness if they are accompanied by functional or postural abnormalities, which generally occur only if the lock involves more than two vertebral bodies. Dynamic radiological studies will give an indication of this. The site (thoracic or lumbar), and the role of the pilot (combat aircraft, helicopter) should be taken into account in the assessment of fitness.

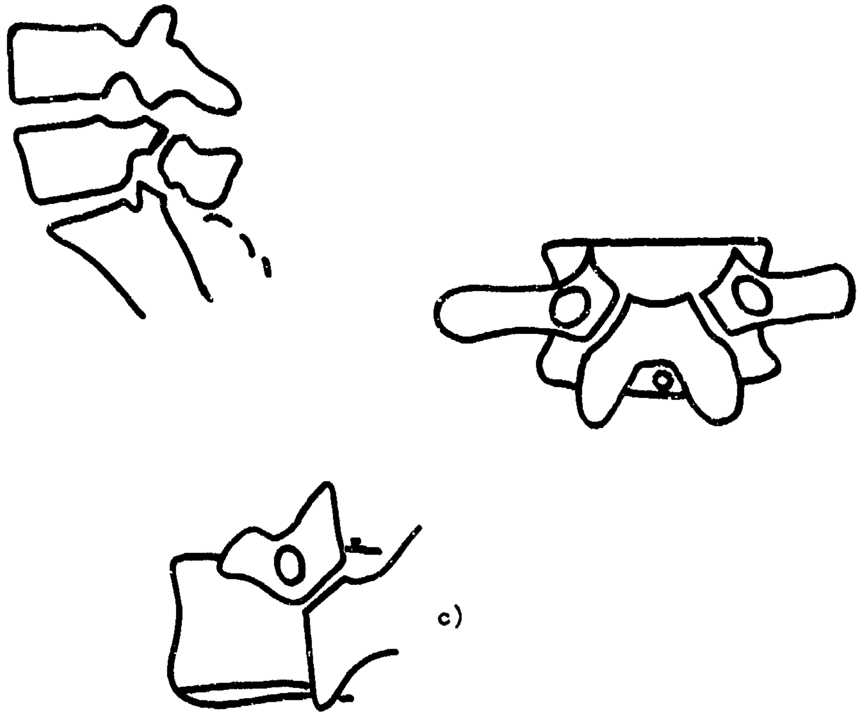

Figure 201. Disruption of the isthmus.
a) lateral b) frontal c) 3/4 view

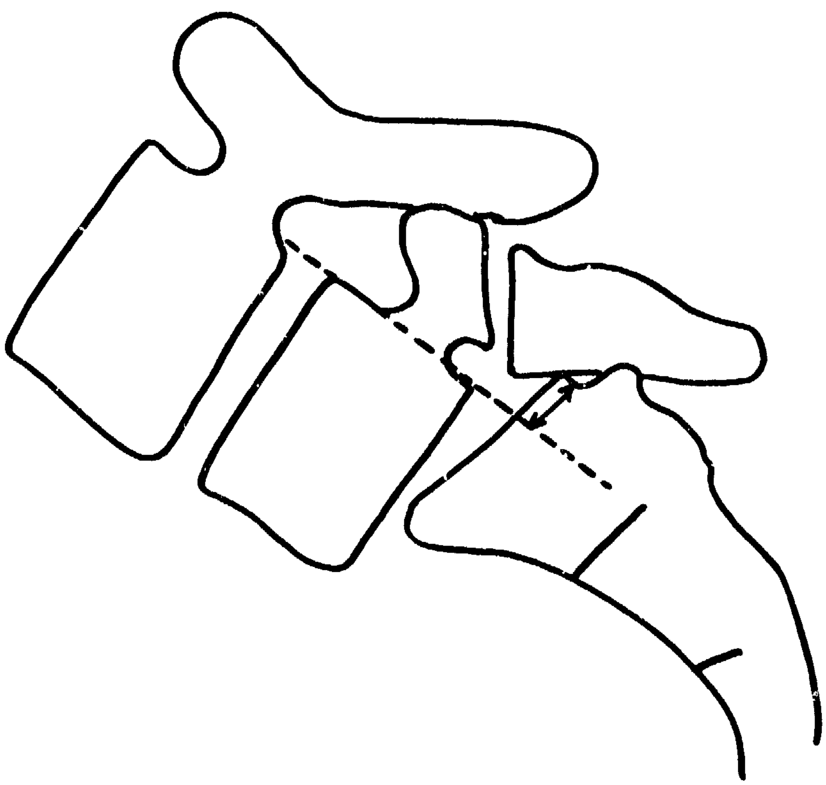

Figure 202. Spondylolisthesis of L5 on S1.

Thus, the existence of a lumbar lock at (L2/L3, for example), which is certainly a rare eventuality in a candidate for helicopter flying, signifies unfitness. On the other hand, this same abnormality in the pilot of a combat aircraft may not, perhaps, merit down-grading, especially if there is no functional impairment and no other associated lesions.

7.1.5.5. Changes Due to Disorders of Development of the Vertebral Body (416)

These less common conditions should not lead to unfitness when the total effect on the spine is moderate or absent. Thus, the anterior corner syndrome, even if multiple (two or three), should not signify unfitness if it is not accompanied by the sequelae of Scheuermann's disease.

On the other hand, the problem of anterior retromarginal hernias is more troublesome, even when they are isolated or few in number (one or two). If they are confined to lumbar sites they should certainly be carefully analysed, taking into account the possible future specialisation (helicopter pilots). In this case, a decision of disability might be made.

7.1.5.6. Complex Congenital Malformations

Easily analysed by supplementary radiological examinations and particularly by tomograms, these malformations whatever their type, denote unfitness for all flying duties. Examples are:

- malformation at the occipito-cervical junction (basal depression particularly)

- vertebral agenesis or hypogenesis (hemi-body, hemi-vertebra, split body).

7.1.6. Acquired Disorders of the Spine (9, 52, 70, 76)

These are progressive conditions of neoplastic, infective (spondylitis) or inflammatory (ankylosing spondylitis) type. Their recognition must be followed by a complete examination and, in most cases, to permanent disability.

The after-effects of trauma (most often fractures) should be differently considered according to whether they are the sequelae of stable fractures (simple anterior wedge compression), or of unstable fractures with injury to the wall of resistance, rupture of the posterior wall, or fracture of the posterior arch. The state of adjacent discs should also be taken into consideration. In the interests of clarity it seems necessary to define the terms "minor" and "major" in relation to the after-effects of trauma.

Among major traumatic after-effects must be included the sequelae of unstable fracture, and of anterior wedge fracture with rupture of the posterior wall, damage to the discs and serious effects on posture. These imply complete unfitness for all posts.

The assessment of the significance of minimal after-effects is best left to the opinion of the expert after clinical and radiological examination. These sequelae are usually compatible with the work of a fighter pilot, for example.

7.1.7. Causes of Disability Determined by Clinical and Radiological Evaluation

Clinical and physiopathological studies confirm that there is a critical spinal segment for each crew station:

- the thoracic spine and thoraco-lumbar junction during ejection from combat aircraft

- the lumbar spine and lumbosacral junction in helicopter flying.

Since these critical segments are different, it is clearly difficult to formulate common criteria of fitness for these two crew types. Thus, there are some causes of disability common to combat aircraft, helicopters and transport aircraft, and others specific to the first two roles (9, 52, 58, 60, 61, 76).

7.1.7.1. Causes of Disability Common to All Flying Roles

These are:

- complex congenital abnormalities

- progressive diseases

- disorders of vertebral geometry in the frontal plane (scoliosis with an angle of more than 25°) and in the sagittal plane (thoracic hyperkyphosis of more than 50°).

7.1.7.2. Causes of Disability Specific to Combat Aircraft Flying (9, 52, 60, 76)

These are:

- postural disturbance in the frontal plane when the angle of the scoliosis is more than 15°. In the sagittal plane assessment of any kyphosis should take account of the presence or absence of sequelae of vertebral osteochondrosis (Scheuermann's disease), when the values lie between 35° and 50°. Above 50°, a decision of unfitness is given

- the sequelae of epiphysitis at thoracic level and conforming to the moderate degree previously defined; slight after-effects and those at the less important lumbar sites are compatible with this type of flying. Note that transitional lumbosacral anomalies and spondylolysis with or without spondylolisthesis of less than 1 cm are compatible with flying a combat aircraft.

7.1.7.3. Causes of Disability Specific to Helicopter Flying (61, 76)

These are:

- scoliosis, when the angle exceeds 15°

- the sequelae of osteochondrosis lead to unfitness if they involve the lumbar region and if the degree of injury is moderate

- some transitional lumbosacral anomalies lead to disability

. if the disengagement is marked, even when symmetry is maintained

. if the disengagement is moderate, with asymmetry at the site of the anomaly

. if there is a new transverse sacral articulation on one or both sides, whatever the type of the anomaly.

Thus, fitness will not be affected if the displacement is moderate, if symmetry is preserved and if there are no new articulations.

- Spondylolisthesis, even if the slippage is less than 1 cm, is a cause of unfitness. Only spondylolysis without spondylolithesis is compatible with employment in this role; the absence of clinical symptoms and the need for well developed musculature must be emphasised.

Tables 7.3, 7.4 and 7.5 summarise the various criteria to be used by the radiologist.

TABLE 7.3

Disturbances of Spinal Geometry (Decision to be taken)

		Combat Aircraft	Helicopter	Transport Aircraft
Thoraco-lumbar	Angle less than or equal to 15°	Fit	Fit	Fit
	Angle between 15° and 25°	Unfit	Unfit	Fit
	Angle greater than 25°	Unfit	Unfit	Unfit
Thoracic Kyphosis	For all values greater than 50° (For values between 35° and 50°, take account of presence or absence of osteochondrotic sequelae)	Unfit	Unfit	Unfit

TABLE 7.4

Congenital Abnormalities of the Spine (Decision to be taken)

		Combat Aircraft	Helicopter	Transport Aircraft
Transitional lumbo-sacral anomalies	Marked disengagement of the pivot vertebra, with symmetrical transitional anomaly	Fit	Unfit	Fit
	Moderate disengagement of the pivot vertebra, with symmetrical transitional anomaly	Fit	Fit	Fit
	Moderate disengagement of the pivot vertebra, with asymmetrical transitional anomaly	Fit	Unfit	Fit
	Unilateral or bilateral trans-sacral new joint, whatever the type of transitional anomaly	Fit	Unfit	Fit
Dissolution of the isthmus	Without spondylolisthesis	Fit	Fit	Fit
	With spondylolisthesis; slippage less than 1 cm	Fit	Unfit	Fit
	With spondylolisthesis; slippage more than 1 cm	Unfit	Unfit	Unfit
Congenital block	Without functional or dynamic disturbance	Fit	Fit	Fit
	With functional or dynamic disturbance	For	Expert	Opinion

TABLE 7.5

Assorted Conditions

			Combat Aircraft	Helicopter	Transport Aircraft
Sequelae of osteochondrosis of growth (Scheuermann's disease)	Minor		Fit	Fit	Fit
	Moderate	Thoracic	Unfit	Fit	Fit
		Lumbar	Fit	Unfit	Fit
	Severe		Unfit	Unfit	Unfit
Retro-marginal hernia; free anterior corner (in isolation)			Fit	Fit	Fit
Major congenital or acquired abnormalities			Unfit	Unfit	Unfit

7.1.8. Conclusion

With regard to fitness for flight, we propose standards related to the spinal segments that are critical for different types of flying. They concern particularly the pilots of combat aircraft and helicopter pilots; fitness for one of these roles does not necessarily signify fitness for the other. As far as flying transport aircraft is concerned, the latitude in respect of spinal fitness appears to us to be very large; there is no specific cause of unfitness provided that the candidate is fit for military service. Under these conditions, it seemed logical to establish a standard for the initial medical examination (SGA A):

1 Fit

0 Unfit

reserved for the pilots of combat aircraft with ejection seats, and to create a standard (SGA H):

1 Fit

0 Unfit

for helicopter pilots.

Fitness under category A or H automatically implies fitness for flying transport aircraft. However, it is possible to be unfit for flying combat aircraft and helicopters and yet be fit as a transport pilot.

In the same way, a candidate with a certain type of transitional anomaly of the lumbosacral junction may be fit for flying in combat aircraft and unfit for helicopters. Of all the categories of fitness that for flying helicopters is the most demanding.

This method of expressing fitness of flying personnel (especially pilots) as a function of their speciality, has not aroused much enthusiasm in France. Nevertheless, General Evrard, Surgeon General of the Belgian Air Force and world famous specialist in aviation medicine, writing in the book "Comparative Study of Medical Fitness Regulations for Flight Personnel Specialites in 9 Military Aircraft of 7 NATO Countries" (AGARD AG 213, 1978 (82)) declares on page 17:

> "In considering different flying duties, each with its own pathology and its own requirements, it is possible to find, even in the presence of certain defects and certain abnormalities, standards compatible with the performance of all airborne missions while still preserving flight safety. On the other hand, trauma to bones and joints has such a place in aviation medicine that very detailed texts seem more desirable than very concise texts, which amount to a few generalities without explanatory comment."

This attempt to specify critical segments is intended to meet some of the imperatives established by Evrard (82).

Supplement to Section 7.1

This supplement presents, in tabular form, the results of 5000 radiological examinations of the entire spinal column, distributed in the following manner:

- 2500 aircrew candidates (series I, obtained from 1970 through 1975)
- 2500 hospital cases (Begin Hospital) (series II, obtained from 1971 to 1978).

TABLE 7.6

	SERIES I		SERIES II	
	Aircrew		Begin Hospital	
	Number of cases	%	Number of cases	%
1. Disturbance of thoraco-lumbar geometry in the frontal plane	1867	74.68	1802	72.1
- Scoliotic posture	518	20.72	485	19.7
- Scoliosis without pelvic disequilibrium	839	34.56	797	31.8
- Scoliosis with pelvic disequilibrium	510	20.40	520	20.8
2. Disturbance of cervical geometry	471	18.84	425	17
- Deviation	329	13.16	312	12.4
- Disharmony	95	3.80	87	3.5
- Disharmony and deviation	47	1.88	25	1
3. Sequelae of Scheuermann's disease	302	12.08	335	13.4

TABLE 7.7

	SERIES I		SERIES II	
	Aircrew		Begin Hospital	
	Number of cases	%	Number of cases	%
4. Anatomical variations	191	7.64	265	10.6
Anterior wedging of:				
L1	102	4.08	110	4.4
L2	35	1.40	55	2.2
D12	30	1.20	35	1.4
Other vertebrae	24	0.96	65	2.6
5. Congenital malformations				
a) Splitting of posterior arch	482	19.82	537	21.4
S1	437	17.48	497	19.8
L5	23		20	
S2	12		14	
C5	2		1	
C6	1		1	
C7	1		1	
D1	0		1	
D12	5		1	
Various			1	

TABLE 7.8

	SERIES I		SERIES II	
	Aircrew		Begin Hospital	
	Number of cases	%	Number of cases	%
5. Congenital malformation				
b) Transitional anomalies	237	9.48	282	11.2
L5	109	4.36	142	5.7
Semi-sacralisation	37	1.48	47	1.9
Sacralisation	72	2.88	95	3.8
S1				
Semi-lumbarisation	26	1.04	65	2.6
Lumbarisation	102	4.08	75	3
c) Dissolution of isthmus	114	4.56	140	5.6
. with spondylolisthesis	76	3.04	82	3.3
L5 on S1	68	2.72	77	3.1
L4 on L5	4		4	
S1 on S2	3		1	
C6 on C7	1		-	
. without spondylolisthesis	38	15.2	58	2.3
L5	31		51	
L4	4		5	
S2	3		2	

TABLE 7.9

	SERIES I		SERIES II	
	Aircrew		Begin Hospital	
	Number of cases	%	Number of cases	%
5. Congenital malformations				
d) Congenital locks (other than transitional anomalies	26	1.04	30	1.2
C2-C3	10		19	
C3-C4	3		1	
C4-C5	1		2	
C5-C6	2		2	
C6-C7	4		3	
C7-D1	2		1	
D9-D10	2		1	
D10-D11	2		1	
e) Rarer anomalies				
. Anterior corner syndrome	28	1.12	50	2
. Anterior retromarginal hernia	46	1.84	35	1.4
. Cervical rib	9	0.36	12	0.4

7.2. RE-EXAMINATIONS

Any lesion can weaken the spine and sensitise it to the action of different stress factors in flight. Some stresses are frequent and inherent in flight (vibrations, accelerations of long duration); others are accidental (ejection in particular or more rarely crash), and they expose the skeleton of the pilot to considerable forces for a very short duration. Moreover, traffic or sports accidents, in their immediate or long term course, sometimes result in disorders of variable severity which can affect the operational performance of pilots.

The conduct of the re-examinations carried out at intervals during the career of flying personnel is very different from that of the initial medical examination. There is no clearly defined and standardised procedure (9). Each patient, and each injury, is a special case and in each, decisions can only be made as a result of medical and surgical considerations.

7.2.1. Fractures and Trauma of the Spine

These occur extremely frequently after varied trauma: road traffic accidents, sports, aviation. Whatever their aetiology, the problems of fitness that they pose are always very difficult.

7.2.1.1. Fractures of the Thoraco-lumbar Spine

Fractures of the thoraco-lumbar spine are seen in aviation after ejection, crash and especially parachuting. They very often alter the strength of the spinal column and decisions concerning fitness depend on the type of fracture.

Two types may be distinguished:

- comminuted fracture

- simple crush fracture.

1. Comminuted Fracture of the Thoraco-lumbar Vertebrae

Watson-Jones (448) has laid stress on some fundamental points. When the anterior edge of a vertebral body has penetrated the fractured body, the spine was in hyperflexion at the moment of the trauma. The interspinous ligaments are torn and the interapophyseal articulations are often dislocated. The vertebral discs immediately above and below the site of the fracture are damaged. These fractures are of the unstable type.

Watson-Jones considers that trauma causing a localised dislocation, crushing of one or more vertebral bodies, ruptured disc, torn ligaments, fracture of the pedicles, interarticular dislocation, partial destruction of the intervertebral foramina or compression of the nerve roots, will probably lead to a syndrome of persistent severe pain, even if the displacement is reduced and the reduction is maintained. These fractures consolidate slowly if conservative treatment is used. Immobilisation in a plaster cast should be maintained for at least 5 months, and sometimes for 6 or 7 months. Union of the vertebral bodies and ossification around the articular processes only develops slowly. Painful symptoms, discomfort, and a feeling of weakness last for a very long time. Functional recovery from a severe comminuted fracture is only seen after several years.

Surgeons try to accelerate this process of healing by intervention to promote fusion of spinous processes and of vertebral laminae. For a doctor responsible for examining such a pilot, the decision is simple. Casualties with comminuted fractures must be classed as unfit to fly combat aircraft, unfit to fly helicopters, and unfit for parachuting (according to their speciality). The vertebral column is no longer capable of sustaining the constant stresses of flight without risk of decompensation and, *a fortiori* , the accidental traumas of aviation (another ejection, crash). Moreover, these patients frequently suffer even in the conditions of normal life, because arthritis supervenes with a frequency that varies with the statistics but which is always high (60-70%). Fracture dislocations should lead to permanent unfitness for all employment as a pilot.

Nevertheless, it is necessary to draw attention to several exceptions to these strict rules, for account must be taken of the psychological make-up of the pilot and his experience (a test pilot, for example). We are following several pilots who were not graded permanently unfit for flying duties. They include two cases of comminuted fracture of D6 (ejection), and one case at D5 (automobile accident). Spontaneous progression towards ankylosis, the rapid appearance of arthritis, and prejudice to the professional career persuaded the experts to award a very limited category. These three fighter pilots were downgraded (transport pilot or pilot of light aircraft). These exceptions have required numerous consultations between physicians and surgeons. The waivers were always for a limited time, and medical examinations and radiographic monitoring have shown, in these very special cases, the sound basis of these decisions in pilots who mainly occupied staff posts, and who, because of this, had much reduced flying duties.

2. Simple Compression Fractures

Rapidity of healing is always helped by the use of exercises appropriate to the clinical case. Pilots can soon be permitted to resume flying, with the positive help of the flight surgeon. The latter must carefully supervise the resumption of a professional activity which is often intense (as in the case of pilots in a fighter squadron). For

helicopter pilots the subsequent course is not always simple, and the return to activity is usually much slower. Because of the magnitude of the vibrations, we think it advisable to carefully monitor the progress of the subjects after the return to flying, to detect the appearance of painful sequelae. Gentle daily spinal exercises which do not aggravate the back pain, indoctrination of the flying personnel who must participate in the treatments but not undergo them, and psychological support always help the operational rehabilitation of these pilots.

The squadron medical officers play an essential, fundamental, and irreplaceable role here. They are nowadays well aware of the benign nature of these simple compression fractures, which for 25 years they were not! Very severe and immediate decisions are no longer necessary, because of better knowledge of the course of these injuries.

7.2.1.2. Fractures of the Cervical Spine

These are most often due to road traffic accidents or to accidents in sport but they do occur, although less commonly, in aviation (parachuting, crash, landing accidents in ejected pilots). They usually consist of fracture dislocations, especially between C5 and C7.

In general, the expert tends to reject the casualties and to class them permanently unfit for all flying duties after clinical and radiological examination.

In isolated fractures of the lateral masses of the atlas, not causing serious modification to the static equilibrium of the spine and producing no clinical effects, a category of restricted fitness - for light aircraft flying - has been suggested, with four renewals.

All cases of fracture dislocation of the atlas-axis, even those treated surgically, do not in our judgement permit a flying career to be continued, even with a limited category.

Isolated fractures of the articular processes, which are sometimes missed in early radiological examinations, should, after clinical and radiological survey (dynamic examination, in particular) and a properly-conducted course of rehabilitation, lead to less stringent rulings.

7.2.1.3. Fractures of the Transverse Processes

These fractures of the lumbar vertebrae, which are often multiple, should, after treatment and muscular rehabilitation, permit the return to normal flying activity. It is known that the temporary period of unfitness is often longer for helicopter pilots than for fighter pilots. Moreover, the resumption of flight in helicopters must be monitored with particular care by the squadron medical officer.

7.2.1.4. Spinal Trauma Without Fracture

The absence of radiological signs does not signify the absence of anatomical lesions to the intervertebral discs and perivertebral ligaments. The development of pain and of deterioration of the disc is always a possibility in the years following ejection or trauma. In these pilots it is often difficult to prove that the traumatic injury is responsible for the occurrence of pain and arthritis. Radiological monitoring at intervals of 6 months, 12 months and 18 months after trauma sometimes serves to detect the rapid development of arthritis.

7.2.2. Vertebral Osteoarthropathy (9, 70, 76)

7.2.2.1. Tuberculous Osteoarthritis

The existence of tuberculous osteoarthritis of the spine (Pott's disease) is easy to demonstrate. In the French Armed Forces (Air Force, Naval Air Force, Army Air Force) this disease is a cause for rejection at the preliminary medical examination. Since radiographic examination of the vertebral column has been a compulsory part of the admission medical, no case of Pott's disease has been observed. A decision of permanent unfitness in active flying personnel will not be taken on biomechanical grounds, but because of the presence of a tuberculous infection which is always liable to be re-activated despite the use of effective medical treatment.

The observation of several cases of spinal tuberculosis in current practice, in civilians or in non-flying military personnel, allows us to state a very firm opinion. There can be no question, even after non-invasive medical treatment or limited surgery, of allowing operational flying activity (fighter aircraft, transport, helicopters) or parachuting. We consider that the only logical decision is permanent unfitness, whatever the seniority, experience or value of the pilot or aircrew member.

7.2.2.2. Other Osteoarthropathies (9, 70, 76)

Other osteoarthropathies (brucellosis, staphylococcal infection) deserve very particular attention. Both cause some destruction of the vertebral bodies, and tend to lead rapidly to ankylosis. We lack experience as far as aviation is concerned, but we have been able to establish that there appears to be no special weakness once the disease is cured. These opinions must, of course, always be based on a complete clinical, biological

and radiological assessment. In some cases, we believe that a limited category can be awarded, taking account of the location of the injury, its severity, the lesions observed, and the specialisation of the patient (combat aircraft, light aircraft, helicopter).

7.2.3. Vertebral Arthritis

SUMMARY

7.2.3.1. General

Arthritis is defined as primary destructive and degenerative change in the articular cartilage, with the secondary appearance of underlying accessory bony lesions, from an inflammatory synovial reaction. Among the sites of arthritis, a very important place must be given to the intervertebral joints.

There are two locations for the arthrotic process in the spine:

- discarthritis, characterised by a degenerative deterioration of the disc, which may or may not be accompanied by anterior and lateral osteophytosis

- interapophyseal arthritis, which is most frequent in the lumbosacral region where the articular processes are close to the horizontal. It is also found in the cervical column. It is characterised by damage to the cartilage, with erosion, ulceration and osteophytosis, sometimes with deformation of the inferior articular process, which may cause an acquired arthritic spondylolisthesis. In this situation, there is often an inflammatory reaction of the articular synovium.

7.2.3.2. Pathogenesis of Spinal Arthritis

Vertebral arthritis increases in incidence with age. Schmorl (416), in a systematic anatomical study, showed that 93% of men and 84% of women between the ages of 50 and 60 years showed signs of disc degeneration, but that there was considerable individual variation. As with arthritis in the limbs, the state of the cartilage and the fibro cartilage varied with the individual. This variability is probably related to genetic factors.

Mechanical factors play some part in the degeneration of the disc, and in that of the cartilage of the interapophyseal articulations.

De Seze (455) particularly stresses the role of mechanical overload in the deterioration of the disc immediately underlying a lumbosacral transitional anomaly, and on the preponderance of disc degeneration in the concavity of the spinal curve where the pressures are highest. Interapophyseal arthritis in the lumbosacral region is most often seen in subjects with a high degree of hyperlordosis, which throws the joints into a horizontal plane where they tend to support the body weight. There is no correlation between the anatomical lesions of arthritis of the disc or interapophyseal arthritis and the clinical manifestations.

Discarthritis, even with very severe osteophytosis, is often totally asymptomatic. Spinal osteophytosis more represents scarring of an old process than current disease.

The pains of disc degeneration are mainly related to movements of the nucleus within a deteriorated annulus fibrosus, fissured with intradiscal hernias which damage the peripheral regions of the disc. These are innervated and therefore potentially painful (De Seze, 455).

7.2.3.3. Cervical Arthritis

Painful symptoms in the cervical spine generally appear between 40 and 60 years of age. They may consist of neckache or of cervico-brachial root pain.

1. Neck pain may appear spontaneously, or on movement of the neck, or from prolonged holding of the neck in a fixed position. The pain may be continuous or intermittent, and is aggravated by movements of the neck. Although often worse at night, they appear particularly in the morning, especially when the cervical spine has been held in a poor position, in lateral flexion badly supported by a bolster or by too large a pillow.

- Clinical examination reveals little. A cervical hyperlordosis is sometimes seen, with limitations of the movements of flexion, extension, lateral flexion and rotation of the neck. Palpation sometimes reveals painful points in the anterior laterocervical regions.

- Radiological examination usually shows abnormalities of the discs at C5/C6 level, with depression of the disc, anterior osteophytosis, condensation of the end plates, deformation and condensation of the unciform processes with osteophytosis clearly visible on three quarter lateral views, and deformation of the intervertebral foramina. This uncino-discal arthritis is also seen at C6/C7. Other vertebral levels are less frequently affected, and if there is isolated damage its cause, which is usually traumatic, should be systematically sought in the past history of the patient.

The interapophyseal interfaces are usually normal. In the upper cervical region there may be nipping, condensation, and osteophytosis of the articular processes, sometimes compressing the cervical roots in the intervertebral foramina. Clinically, interapophyseal arthritis gives rise to high cervical pain with radiation to the occiput, and to vertigo with limitation of the movement of the neck.

2. Cervico-brachial root pain occurs most frequently as a complication of cervical arthritis, of which it is sometimes the first and presenting symptom. Often initiated by trauma, it develops in the days or weeks following the injury. Very severe pain, appearing suddenly or progressively, and made worse by lying down, wakens the patient at night. The distribution of the pain reveals the site of the compression; C5 - outer surface of the shoulder and the arm; C6 - outer border of the shoulder, arm, and the forearm down to the thumb and sometimes the index finger; C7 - shoulder, arm, forearm, middle and ring fingers, and sometimes also the index finger; C8 - medial aspect of the shoulder, the arm, forearm, wrist and ring finger.

The root distribution of these painful symptoms is usually imprecise. Radiation to the scapulae or the front of the thorax can occur, and sometimes presents difficult diagnostic problems. The pains are accompanied by sensory disturbance in the form of paraesthesia, but there is generally no motor deficit. The tendon reflexes may be slightly reduced in the affected territory. Sometimes there is hypo-aesthesia in the distribution of the root. Involvement of the cord is a very rare complication of cervical arthritis.

Treatment consists of immobilising the neck in a cervical collar and the administration of a non-steriod anti-inflammatory drug throughout the painful phase. Resort to intrathecal corticoid therapy is rarely required, and surgery is indicated relatively rarely.

7.2.3.4. Thoracic Arthritis

Thoracic arthritis, like that in the cervical and lumbar regions, is very common. It is often associated with lumbar arthritis. This variety of arthritis is frequently clinically silent.

A regular, relatively small thoracic hyperkyphosis is sometimes observed. Radiologically, the interfaces are narrowed especially in their anterior part, with anterior and lateral osteophytes especially at right angles to the spine. The vertebral end plates are often irregular and condensed. This thoracic arthritis is a frequent complication of the sequelae of Scheuermann's disease (spinal dystrophy of growth).

7.2.3.5. Lumbar Arthritis

Lumbar arthritis, often latent, is extremely common between 30 and 60 years of age.

Clinically, its painful functional manifestations are often brought on by trauma.

1. Disc Arthritis

Clinically, disc arthritis is manifested by very frequent pains, either acute (lumbago), or chronic.

Lumbago is a pain which may be spontaneous or provoked by an unguarded movement, a lifting effort or trauma. Of abrupt onset, the pain is usually in the lower lumbar region, extremely intense, and without radiation. There is a feeling of "locking" of the lumbar spine. The pain is increased by movements or coughing, and is eased by bed rest.

The pain and functional discomfort disappear within a few days, but the lumbago frequently recurs. Later attacks, sometimes developing over a long time, result finally in chronic lumbar pain.

Chronic lumbar pain follows one or more attacks of acute lumbar pain, or may appear *de novo*. The pain is in the lower lumbar region. It is increased by lifting effort, the upright posture, the sitting posture, prolonged walking or riding in a vehicle, and it disappears with bed rest. It sometimes radiates to the buttocks. Apart from pain on palpation of the spinous processes or the spaces between them, and the paravertebral regions at the level of L4 and L5, clinical examination is normal. There is sometimes a moderate limitation of movement of the spine in anterior flexion, in lateral flexion, and in extension. Radiologically, the spine may be normal. Quite often there is narrowing of one, or less commonly of several, interfaces with a more or less large anterior osteophyte sometimes accompanied by condensation, usually lateral and at the level of L4/L5 or L5/S1. Vertebral anomalies, unilateral or bilateral transitional lumbosacral anomalies, spondylolysis with or without spondylolisthesis, and the sequelae of Scheuermann's disease are sometimes indicated by the appearance of sciatic root pains in the distribution of L5 or S1, and more rarely by pains in the leg.

2. Interapophyseal Arthritis

Interapophyseal arthritis occurs mostly after the age of 50. It is usually located at L4/L5, L5/S1 and less commonly at L3/L4, and is often secondary to a lumbar hyperlordosis.

- Clinically it presents as a quite characteristic lower lumbar pain which is particularly acute on prolonged sitting, prolonged walking, or carrying loads. It wakes the patient at night, but a change of posture then brings temporary relief. It is sometimes characterised by a picture of stenosis of the lumbar root canal, with an intermittent root claudication syndrome; the pain has a sciatic or crural distribution on one or both sides but not passing below the knee. It appears after walking a set distance (a few hundred metres), and disappears on stopping or when the patient bends forward. It reappears when walking is resumed. This pain is often accompanied by paraesthesia. Examination sometimes reveals points painful to pressure in the region of the articular processes or in the paravertebral regions. There is no Lasegue's sign. Forward and lateral flexion are painless, but extension is acutely painful.

- Radiologically, frontal views show increased density and hypertrophy of the articular masses. Lateral films, and especially three-quarter views, confirm the condensation, hypertrophy and deformation of the articular processes with narrowing of the interfaces. Quite frequently, there is an arthritic spondylolisthesis of L4 on L5, or less commonly of L5 on S1. In the common event of associated disc arthritis, one or more backward displacement may be seen. Tomograms confirm the presence of narrowing of the lumbar root canal, and tomodensitometry allows detailed study of this stenosis at the level of the interapophyseal articulations.

The treatment of lumbar arthritis calls for careful physical management, including rest during attacks, analgesics, anti-inflammatory drugs, and many days of rehabilitation exercises, together with correction of the lordosis, and possibly loss of weight. When stenosis of the lumbar root canal causes painful symtoms which resist treatment, laminectomy may be necessary, and this leads, *ipso facto*, to unfitness for flying duties.

7.2.3.6. Aeromedical Aspects of Arthritis

1. General

There are very few studies devoted to verebral arthritis in flying personnel.

To our knowledge the only publications concerned solely with the spine which make reference to it are:

AGARDograph No. 140 by R.P. Delahaye et al (52).

AGARD Advisory Report No. 72 by R. Auffret and R.P. Delahaye (9).

However, arthritis is the spinal disorder which causes the most aeromedical problems, with the exception of fractures of the spine. There are several reasons for this:

1. Its incidence is high in our countries.

2. It appears, in many cases, to be closely linked with flying duties, raising questions of liability and compensation.

3. Because of this, it can have implications for the employment standards of flying personnel in certain specialities.

2. Incidence of Vertebral Arthritis in Flying Personnel

Spinal arthritis is relatively common after the age of 40 years, at least as an asymptomatic radiological finding. It is not unusual to detect it at markedly lower ages, down to 30 years or even less.

In these circumstances, it is difficult to determine if its incidence is higher in the selected population represented by flying personnel.

Several authors have, however, tried to answer this question. Their studies have specifically concerned:

- the lumbar spine of helicopter pilots (see Chapter 6.1.)

- the cervical spine of figher pilots (see Chapter 6.2.).

The studies so far carried out have involved small samples and cover a limited time. It is at present impossible to reach a definitive conclusion, both because of significant changes in the nature of the flying task (helicopters) and because of improvements in technology (lower level of vibration in the newer helicopters).

3. Role of Flight in the Development of Arthritis

Can flying duties be directly responsible either for the initial appearance or for the exacerbation of vertebral arthritis? At the extreme, can it be called "professional pathology" in some cases? Can the lesions observed be attributed to flying service, and should compensation be considered?

It is known that repeated microtrauma can be responsible for the development of arthritis, and this is certainly true in the spine.

In aviation, three factors can play a part:

- vibrations

- accelerations

- postural factors (poor position of the pilot).

We shall not discuss further these harmful factors, which have already been analysed (Chapter 4).

In practice, a distinction must be made between:

- the helicopter pilot, who is particularly exposed to vibration and to postural factors,

- the fighter pilot, who is particularly exposed to accelerations.

The Helicopter Pilot

Helicopter pilots appear to be especially vulnerable to lumbar arthritis.

Clinically, the spinal pain is almost always acute or chronic backache, with or without sciatic pain.

According to Delahaye et al (75), radiological arthritic lesions are frequent in helicopter pilots with backache. They particularly affect the region from L2 to L5. They usually appear as a reduction in the disc space, with anterior marginal osteophytes.

It remains, however, difficult to incriminate flight directly in the development of lumbar arthritis in helicopter pilots, for at least two reasons:

- there is considerable individual variation in the development of arthritis and, to our knowledge, there have not yet been large scale comparative longitudinal studies between helicopter pilots and a control population

- it is difficult to establish a relationship between lumbar backache and the radiological lesions observed; in fact, we have been able to establish, along with many others, that pilots being evaluated hide their symptoms for fear of losing their flying category; in contrast, when motivation is lost for various reasons, in particular psychological ones, there is often an exaggeration of the backache.

The Combat Pilot

Above all, the harmful factor here is +Gz acceleration.

Normally, the cervical spine is most vulnerable. During accelerations it must, in fact, support the weights both of the head and of the helmet, which is sometimes heavy. At the same time, manoeuvres carried out to combat the cardiovascular effects of acceleration decrease the contact between the back and the fixed plane (the seat) which could give it support.

Like other authors, we have collected several observations of cervical pain brought about by accelerations during aerobatics. In these cases, in which radiography has shown clear signs of arthritis, the accelerations have at least been at the root of the painful episode.

The possible role of accelerations should be particularly considered when arthritic changes are discovered in a young subject (30 years or less) and when their site is unusually high (C2/C3, C3/C4, C4/C5 (52)).

Disc Arthritis; A Future Disease of Combat Pilots?

The new generations of combat aircraft (F-16 and Mirage 2000, for example) will expose the pilots repeatedly to accelerations of long duration. It is timely to ask whether the intervertebral disc will suffer during such accelerations and whether, together with cardiovascular and pulmonary problems, vertebral problems will appear - in particular, that of disc arthritis?

Moreover, to provide greater manoeuvreability, technology has produced so called "unstable" aircraft supported by an electronic flight control system. Failure of this regulating system can expose the pilot to a succession of high accelerations, alternately positive and negative, which may exceed 9 Gz. In such a situation, called "induced oscillation" a pilot who avoids a fatal accident cannot entirely control his body. He is literally thrown about like a puppet, and his spinal column is especially susceptible to damage.

7.2.3.7. Decisions on Fitness

1. Acceptance as Aircrew

At the age of acceptance for flying training, arthritis poses practically no problems because it does not exist. The sole concern of the expert is to detect anomalies of vertebral structure or geometry which might favour its appearance.

2. Re-examinations

During a flying career, isolated radiological anomalies without painful symptoms do not, in theory, present any problem of fitness. It must again be re-iterated here that there is no correlation between the extent of radiological signs and functional disturbance. The problem of fitness has different aspects related to the flight speciality and to treatment. In the pilot of a transport aircraft, the clinical manifestations of arthritis, which are usually associated with excess weight and a sedentary life, lead at worst to a temporary disability, calling for appropriate therapy in case of pain.

If obvious radiological signs of arthritis in a helicopter pilot are associated with repeated episodes of severe pain, a ruling of permanent incapacity should be carefully discussed, because the patient may eventually demand reversal of the decision. In such cases, of course, account must be taken of the age, the radiological appearances, the therapeutic measures already adopted, and the workload.

At present it is generally accepted that backache appears with average flight times of:

- 30-40 hours per month
- 3-4 hours per day
- 1 hour 30 mins of continuous flight.

There are considerable individual variations according to the subjects and their motivation, but these values should not be exceeded when radiological evidence of arthritis exists.

In the fighter pilot, the question of fitness is generally governed by tolerance of accelerations. In this respect, tests on a centrifuge can be useful for assessing the efficacy of treatment and the possibility of a return to flight after the temporary suspension needed to permit treatment.

As in the preceding case, the decision on fitness or unfitness will be a function of many factors (age, degree of functional disorder, radiological appearance of the lesions). Particular attention must be paid to signs of disc arthritis, a condition which is known to be quite sensitive to accelerations, while severe osteophytosis may be accompanied by a good tolerance of those same accelerations.

When a fighter pilot has signs of serious disc involvement (marked narrowing) it must always be borne in mind that he may have to eject, and that the affected intervertebral joint may be subjected to an abrupt and very high load.

7.2.3.8. Fitness and Treatment

Painful arthritic attacks are relieved by rest and analgesics, with anti-inflammatory and relaxant drugs as required. This is later generally supplemented by physiotherapy to restore satisfactory flexibility of the spine and to strengthen the paravertebral muscles.

The use of this treatment leads, in many cases at least, to a fairly short period of temporary grounding which has no effect on the career.

Surgical treatment raises problems of disability, especially in fighter pilots.

The surgical cure of a herniated disc is sometimes necessary, and should be carried out by a surgeon who is aware of the aeromedical problems or who is advised by a flight surgeon. A laminectomy leads to permanent unfitness for fighter aircraft, and especially for ejection seat aircraft. It is possible to relieve a herniated disc without laminectomy, or with a minimal laminectomy, without significant bony or ligamentary damage. The results must be judged on the clinical findings (absence of neurological or sensori-motor sequelae) and by tomography. The surgery should be followed by prolonged physiotherapy to restore a good paravertebral musculature.

With these provisions, we have been able to operate on three fighter pilots for low lumbar herniated disc and to restore them to fitness for flight.

Conclusions

Vertebral arthritis, is a commonly encountered disorder that rarely affects the fitness of flying personnel.

Among the unfavourable factors must be noted:

- roles in which the flying duties impose a stress upon the spine; these mainly comprise helicopter and combat pilots

- painful functional disturbance, unrelated to radiological signs

- radiologically, severe involvement of the discs

- therapeutic considerations, which under favourable conditions do not exclude surgery.

7.2.4. Ankylosing Spondylitis

SUMMARY

Ankylosing spondylitis is the commonest chronic inflammatory rheumatic condition in man. It affects the entire locomotor system, but especially the spinal column, the sacro-iliac joints and the joints of the lower limbs.

7.2.4.1 Aetiology

Although the aetiology and pathology of the disease still remain obscure, recent work has shown that there is a specific genetic background, denoted by the histocompatibility antigen HLA B27, which is present on average in about 80% of affected subjects, while the percentage is only approximately 4% in caucasian controls.

The incidence of ankylosing spondylitis is at least 1 in 2000 on the average (in western countries). It varies greatly between geographical regions, living conditions, and hygiene.

The age of clinical onset, which is somewhat difficult to determine, averages 26 years.

Ankylosing spondylitis selectively affects males (9 out of 10).

Geographical distribution: Ankylosing spondylitis is very unevenly distributed over the surface of the globe, but is particularly common in the countries which border the Mediterranean. Conversely, it appears to be very rare in Black Africa. This peculiar geographical distribution strongly points to the presence of an intrinsic factor related to the environment, or to an ethnic factor, or to both.

Predisposing Factors (302)

. Poor hygienic conditions account for the high incidence of spondylitis seen during and after wars.

. Infections of the urinary and digestive tracts, and even some venereal infections, may lead to ankylosing spondylitis.

The Fiessinger-Leroy-Reiter syndrome, which is also related to the HLA B27 antigen, leads to the fairly rapid development of ankylosing spondylitis in 30-50% or more of cases. Psoriasis is also quite often associated with ankylosing spondylitis.

. Haemorragic colitis, Crohn's disease, Whipple's disease and Behcet's disease are also associated with anklosing spondlyitis.

. Trauma is sometimes a precipitating factor leading to, or exposing, ankylosing spondylitis.

7.2.4.2. Clinical Features (302)

1. At its onset, ankylosing spondylitis presents as pains in the buttocks, lower lumbar, thoracic, intercostal and cervical regions and unilateral, bilateral or shifting sciatic pain of which the timing (the second part of the night) is especially suggestive but variable. These manifestations follow one another or are associated in time in a way that varies considerably from one case to another. The onset of the disease may also be denoted by symptoms in peripheral joints (25% of cases, according to Forestier) usually in the lower limb and less commonly in the upper limb, by ocular disorders (iritis), or by pain in the heel, which indicates involvement of the calcaneum.

2. In the active state, that is, after several months or years, and especially if the disease has not been recognised and treated, early deformation of the spine with cervico-thoraco-lumbar kyphosis is seen, with forward projection of the head and a reduction in the expansion of the chest.

7.2.4.3. Radiology

Standard radiological examination shows, at the outset, bilateral sacro-iliac involvement with erosion of the iliac crest, apparent enlargement of the interspace, and then consolidation and finally total ankylosis. From the start, careful examination of the spine reveals the outline of syndesmocytes especially at the thoraco-lumbar junction. Later, the diagnosis will be evident from the rows of syndesmocytes, which give the column the appearance of a "bamboo stalk", and calcification of the interspinal ligaments and interapophyseal articulations, which give the classicial "three rail" picture.

7.2.4.4. Biochemistry

The sedimentation rate may be increased but there is no close correlation between this and the clinical development.

7.2.4.5. Clinical Forms

The clinical, radiological, and developmental polymorphism of ankylosing spondylitis is altogether remarkable. Involvement of the limb joints is quite frequent in the course of development as well as at the outset. In particular, the severity of damage to the hip joints determines the functional prognosis. Spondylitic lesions of the discs are found in 5% of cases. They can take on the appearance of Pott's disease, the differential diagnosis from which is sometimes very difficult.

7.2.4.6. Complications

The course of the disease is sometimes studded with numerous complications; ocular (iritis), which may be the initial symptom, cardiac (aortic insufficiency, disturbances of atrioventricular conduction), pulmonary (apical pulmonary fibrosis), neurological (peripheral or central), and laryngeal. Spinal fractures involving discs or bodies, which are always serious at the cervical level, are not exceptional and may be responsible for some neurological complications. Amyloidosis is seen in 2-4% of cases.

7.2.4.7. Development

Development proceeds very slowly, either in a continuous fashion (in one third of cases), or in steps, and may be punctuated by the complications already listed.

7.2.4.8. Diagnosis

The diagnosis of ankylosing spondlyitis is frequently very difficult. In the early stages, radiological changes may be of delayed appearance. Functional signs remain atypical for a long time, with trivial spinal pains of a mechanical character and intractable sciatica of root origin. These lead all too often to ill-judged specialised examinations (radiculography, sometimes repeated) or even to premature and inopportune surgical intervention.

The diagnosis rests on data obtained from carefully analysed history-taking, on the results of meticulous clinical examination and of high quality radiograms, and possibly on bone scintigrams which particularly show sacro-iliac involvement. Measurement of the HLA B27 antigen which denotes the existence of a "spondyloarthritic tendency" is sometimes a valuable added pointer to the diagnosis.

7.2.4.9. Aeromedical Aspects of Ankylosing Spondylitis

1. General

Before considering the questions of fitness raised by ankylosing spondylitis, some basic principles should be repeated.

This disease affects the young man, and does not have a uniform geographical distribution. It particularly affects those living around the Mediterranean basin.

In difficult living conditions, like those of armed conflict, the disease can appear in any country. The Finnish epidemic in the Second World War is one example.

The incidence among flying personnel is, accordingly, variable from one country to another depending on the circumstances. Although it is not well documented, it can be considered to be very low at present.

Aetiologically the possible role of trauma as an initiating or aggravating factor must be stressed. As a general rule, the aetiological influence of trauma must be accepted if it is severe and if the sponylosis develops a very short time after it (Doury, 3C2).

The role of trauma must be taken into account when fitness is considered:

- in helicopter pilots exposed to vibration and to postural problems

- in fighter pilots who are exposed to accelerations and are possible candidates for ejection.

Finally, before a decision of flying fitness is made, the following must always be kept in mind:

- that the ankylosing spondlyitis may be a general disease which extends beyond the confines of the spine

- that it can uncover syndromes which are of themselves causes of unfitness.

2. Acceptability for Flying Duties

The discovery of ankylosing spondylitis during the initial medical examination must imply permanent unfitness for all employment as flying personnel. This decision is justified by uncertainties about the development of the disease.

3. Re-examinations

It seems reasonable to base decisions of fitness on two criteria:

- the clinical form of the disease;

- the flying speciality.

Clinical Criteria

Four elements should be taken into consideration:

- the severity of the spinal involvement

- lesions outside the spine

- aetiology

- treatment.

Severity of Spinal Involvement

It is known that there is not always a close correlation between the functional disorder and the radiological signs of this disease, which is more peri-articular than articular. It is also very important to take into consideration the functional impairment related to the pain, and especially to the spinal rigidity. Fixed deformities, if they exist, are a cause of unfitness for all duties.

Extra-spinal Lesions

These are of grave significance, and entail temporary or permanent unfitness for flight. It is essential to take particular account of:

- involvement of joints other than the spine, especially the hip joints

- ocular complications

- cardiac disorders. Aortic insufficiency is, in practice, rare. Disturbances of rhythm and conduction, which are more frequent should be systematically explored by a continuous, 24-hour, record of the ECG

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- the respiratory effects of spinal lesions should be systematically studied by spirography, whatever the radiological picture; a reduction in vital capacity and in forced expiratory volume of the order of 15-20% in a transport pilot should place his flying category in question

- the existence of inflammatory conditions should also be taken into consideration. The presence of an inflammatory syndrome with an accelerated sedimentation rate and elevated levels of fibrinogen and alpha-2-globulins, call for bed rest and, therefore, for temporary unfitness.

The intestinal or abdominal syndromes mentioned above imply unfitness for employment as flying personnel in any role.

Fitness and Treatment

The principles of treatment comprise:

- spinal exercises

- non-steroid anti-inflammatory agents (of which phenylbutazone is the drug of choice), carry iatrogenic risks, especially to the digestive tract. Ankylosing spondylitis is a chronic disease which evolves continuously or in stages; medication will therefore be frequent and prolonged, and this must weigh heavily in the decision of long term fitness. As a rule, the use of any new anti-inflammatory treatment should entail temporary grounding, with avoidance of flight until tolerance of the drug can be assessed.

Aeromedical Criteria

Helicopter Pilots

The flying duties of the helicopter pilot expose the vertebral column to a constant load, and even to repeated microtrauma. Taking account also of the frequency of backache in such pilots, it is legitimate to impose a ruling of permanent unsuitability for the role. Not to take this step if, for example, the patient declares that he is symptom free, is to risk the later arrival of a difficult medico-legal problem. At best, a category of temporary unfitness may be awarded in certain cases.

Fighter Pilots

In fighter pilots our attitude is the same, taking account this time of the stress represented by acceleration and the risk of ejection. The discovery of ankylosing spondylitis, even if the condition is well tolerated, should lead to permanent unfitness. As before, a reduced category for a period of no more than 1-2 years can be awarded to cases who are at the end of their career and who do not present with a severe clinical picture.

The introduction into service of new high performance aircraft is a supplementary argument for recommending permanent unfitness of combat pilots suffering from ankylosing spondylitis.

Transport Pilots

In transport pilots the vertebral column is not particularly vulnerable; in them, the clinical state should be the deciding factor.

7.2.4.10. Conclusions

Decisions of fitness for flight in relation to ankylosing spondylitis should be flexible, depending upon the case. It is important to take account of the clinical form of the disease and the nature of its course, which can only be assessed after some delay. In consequence, it is often necessary to temporise and to wait for several months before making the final decision.

The following should be considered especially unfavourable in relation to fitness for flight:

- specific roles, such as helicopters or combat aircraft

- fixed rigidity of the spine and, even more, deformity

- extra-spinal involvement

- severe inflammatory syndromes

- the prospect of possibly rapid development

- the recognition of a specific aetiology

- the requirements of treatment.

7.2.5. Surgical Intervention

7.2.5.1. Laminectomy (9, 70, 76)

Whether it is elective or urgent, a laminectomy is a surgical operation the purpose of which is to explore or to decompress the spinal cord. It results in great instability, which is even greater when it involves several laminae and when it is extended laterally towards the articular processes. The reason for the laminectomy (spinal compression, tumour) may of itself be a cause of permanent unfitness.

After laminectomy, permanent unfitness for all flying duties should be indicated. The risk of imposing the new traumas of a flying career upon a spine already weakened appears to us to be too great.

7.2.5.2. Treatment of Herniated Disc (9, 70, 76)

This involves an operation which, usually, does not greatly alter the strength of the spine. Before taking the decision, the experts should analyse carefully the findings at operation and use the results of clinical and radiological examination as a basis. They should require that the operation involved no more than a minimal laminectomy, that the diagnosis of a herniated disc was confirmed, and that the intervertebral disc was well curetted. The clinical result should be perfect, with complete restoration of integrity. In particular, there should be no residual paraesthesiae or persistent pains. Tomograms should show the presence of satisfactory secondary bony changes.

On the other hand, if the damage to bones or ligaments is severe, rulings of unfitness for employment as a pilot of combat aircraft or helicopter, or as a parachutist, must be given. If the removal of the herniated disc meets the criteria described above, a full flying category can be maintained.

7.2.5.3. Treatment of Spondylolisthesis (9, 70, 76)

This vertebral anomaly can be surgically treated by ablation of the posterior arch, but imbalance of the function of the spine is produced. The post-operative results of this technique are often mediocre, because pain persists. The flying of helicopters must be prohibited, and a decision of permanent unfitness for all flying duties must sometimes be made.

Other techniques (especially anterior arthrodesis) can be used, but we have not had the opportunity to assess their effectiveness against the pain. If there are no root signs, a full category can be maintained.

7.2.6. The Problem of Repeated Ejections (201, 223)

We have had the opportunity to follow, medically and radiologically, a pilot who had ejected three times. The first two ejections produced fractures at different levels (thoracic in the first, upper lumbar in the second). The third ended in a complex fracture of both bones of the leg. Moreover, several pilots have ejected twice. These repeated traumas always produced uncomplicated compression fractures of the spine, and a return to flying was permitted after consolidation had occurred. It is very interesting to study these repetitions of trauma. So far, it is possible to say that spinal fracture does not affect the same vertebra to the extent that it does in repeated simple fractures not leading to serious change of posture. These cases of multiple ejections deserve to be collected together and published as a special series. In some air forces, a ruling of unfitness is made after the third ejection, for psychological reasons. For our part, we consider that the number of cases observed is still too small to justify a definitive statement. Moreover, we do not know the delayed effects of ejection (44). We have been studying their development since 1960 (66).

Conclusion

Decisions on the retention of a flying category, of downgrading, or even of unfitness, should also be appropriate to the particular clinical and psychological situation. Consultations between physicians, radiologists and surgeons should carefully weigh the known risks and the need to safeguard the legitimate interests of the aircrew and of the Service.

Moreover, these problems of fitness change with time, because account must be taken of progress in medicine and in surgery, and also of new patterns of flying activity (modern combat aircraft with high accelerations of long duration).

CHAPTER 8 - MEDICO-LEGAL ASPECTS OF SPINAL DISORDERS IN AVIATION MEDICINE

P. Doury, R. Auffret and R.P. Delahaye

SUMMARY

"In pilots, the appetite for compensation is generally employed more to regain a flying category than to plead for a pension."

R. Auffret, Ch. Gignoux, R.P. Delahaye (10)

The medico-legal aspects of spinal disorders in aviation medicine, are all too often misunderstood, and merit special study. In fact, throughout their career, flying personnel jealously guard their fitness rating for flight, not just for reasons of finance or of promotion but, primarily because of their love of the aviation environment, or so it usually seems. This spontaneous tendency to "play down" all symptoms so that the flying category will be retained can all too often make significant symptomatology disappear entirely. By association, that is, by continuity of action and effect, some vertebral pains can be positively attributed to the stress of aircrew duty, or as the consequence of the chronic action of the harmful factors of flight. Vibration plays an even larger role than was thought to be the case 30 years ago.

We shall consider in turn;

- trauma and intervertebral arthritis;

- trauma and inflammatory rheumatic conditions;

- spondylolisthesis and its association with trauma.

8.1. TRAUMA AND INTERVERTEBRAL ARTHRITIS

Arthritis of the spine is an extremely widespread condition. Mechanical factors play an important role in its genesis. The problem of post-traumatic arthritis therefore arises.

A distinction must be drawn, depending on whether there was a recent fracture in the preceding trauma, or whether the trauma, despite its violence, did not produce fractures.

8.1.1. Verebral Trauma Without Fracture

8.1.1.1. Arthritis and Trauma

The overloading of the intervertebral disc and the interapophyseal articulations by the microtrauma of daily life, possibly enhanced by postural disorders or by congenital vertebral anomalies, accounts for the development of intervertebral arthritis.

The properties of the cartilage, which are probably linked to genetic factors, explain why the existence, the age of onset, and the degree of degeneration of the intervertebral discs and of the interapophyseal articulations vary so widely from one case to another.

Even if the arthritis can incontrovertibly be related directly and almost exclusively to a single severe trauma to the spine, it is often extremely difficult to prove this direct and exclusive link as a basis for possible compensation.

Even if recourse is made to the argument that, from statistical studies, the incidence of intervertebral arthritis is higher in a group of subjects exposed to occupational spinal overload (as is the case with helicopter pilots) than in a population of control subjects, it cannot follow, *ipso facto* , that membership of that group constitutes a proof that in a given individual the arthritis is directly and exclusively related to the factor of occupational stress.

For a single major trauma, the problem is apparently more simple. Nevertheless, the expert must produce proof of a direct and exclusive link between the trauma and the succeeding intervertebral arthritis. It is therefore necessary to possess precise and indisputable criteria for establishing and confirming the direct and exclusive responsibility of trauma for the origin of intervertebral arthritis.

8.1.1.2. Post-Traumatic Cervical Arthritis

The following case history is interesting in this regard, because it seems to demonstrate the authenticity of post-traumatic spinal arthritis.

Case

C, an ex-pilot in the air force, aged 61 years, had suffered a major accident in 1954; a crash during an operational flight. He was thrown from the aircraft, which exploded soon afterwards. When he was picked up he was suffering only from a few apparently minor contusions and ecchymoses.

Eight days after the accident the patient complained of acute, diffuse cervical pains without radiation. Radiograms of the skeleton, and notably of the cervical spine, showed no abnormality. The painful episode lasted for 15 days.

From 1954 to 1956, the subject had no complaints.

In 1956, while making an unguarded movement, he suffered a fresh attack of acute cervical pain. New radiographs of the cervical spine showed very severe cervical arthritis with compression of the disc of C6/C7, arthritis of C5, C6 and C7 with increased density and deformation of the uncus, and osteophytes distorting the intervertebral foramina.

Since 1956, the patient has had recurrent attacks of left-sided cervico-brachial root pain, with headaches, cervical pain, dizziness, tinnitus and painful limitation of movement of the cervical spine.

Supplementary ophthalmological, otorhinolaryngological and electroencephalographic examinations are normal.

Despite the delay of 2 years between the trauma and the demonstration of the cervical arthritis it appears that the role of trauma in the genesis of this very severe and newly-developed cervical arthritis can be admitted in this case.

In a paper presented to the IV International Congress of Transport Medicine, Doury and Pattin (300), demonstrated the rarity of post-traumatic cervical arthritis, based on a retrospective study of a series of 100 cases of arthritis. Of these, 91 had never experienced the slightest trauma. Nine had cervical trauma during their fairly recent past history (1-7 years). In 7 cases, the specific trauma was overstretching in the sagittal plane in 6 cases and lateral impact in 1 case; in 2 cases it was not defined. The two groups (91 without trauma and 9 with trauma) did not differ in respect of age, sex, functional symptomatology and radiological changes. The latter were centred exclusively on C5/C6/C7, with a nearly equal incidence of anterior osteophytosis (three quarters of cases) single or multiple narrowing of discs, arthritic deformation of the uncus (three fourths of cases) and interapophyseal arthritis (one third of cases). It must be added that in 6 cases out of the 9, the patient knew of the cervical arthritis before the accident. The clinical and radiological progress did not differ appreciably in the two groups.

8.1.1.3. Criteria for the Diagnosis of Post-Traumatic Arthritis

To support a possible traumatic attribution of an intervertebral arthritis, the following conditions must exist together (300):

1. Functional changes appearing immediately after the accident or after a short latent period of several days to several weeks.

2. Radiological integrity of the spine at the time of the trauma (apart from disorders of spinal posture, the interpretation of which is difficult).

3. The appearance, in the weeks or months following the trauma, of ostephytosis, or of a narrowing of the disc spaces, or of an interapophyseal arthritis with condensation and narrowing of one or more spaces.

4. The unusual site of the spinal injury; C2/C3 or C3/C4, or even C4/C5, or, more rarely, C6/C7.

5. Obvious exaggeration of radiological abnormalities, which may have existed prior to the trauma, during the weeks or months which follow it.

8.1.2. Spinal Trauma With Fracture

The causal relationship between the accident and the vertebral fracture is generally not in dispute for fractures discovered immediately after the trauma of an aviation incident: crash, ejection, parachuting, accident from induced oscillation (pumping). When radiological examination is carried out systematically, fratures without clinical signs will not pass unobserved.

Spinal fractures are sometimes complicated by vertebral arthritis, but this development is not invariable. It only appears if the intervertebral disc has been involved in the trauma.

This post-traumatic arthritis occurring in subjects with vertebral fractures does not have specific clinical or radiological characteristics.

The criteria defined by Doury and Pattin rightly lay stress on the frequency of damage to the disc space immediately above the fracture, where an anterior corner is often detached. For example, a fracture of L1 may be accompanied by a narrowing of the D12/L1 disc space.

The signs of vertebral arthritis appear very early, in the form of osteophytosis (the most frequent finding) or as syndesmophytosis. We have followed one case (238) where the arthritis appeared a month and a half after particularly severe trauma (ejection at 650 knots and landing in a coma). The delays in the appearance of arthritis after fractures varies from several weeks to 6-12 months after the most severe trauma.

8.2. TRAUMA AND INFLAMMATORY RHEUMATIC CONDITIONS

8.2.1. Observations

The problem of the connection between trauma and the occurrence of an inflammatory rheumatic condition is very important.

The incidence of post-traumatic rheumatoid diseases is low; of the order of 3-4%, depending upon the cause. Some rare cases of acute rheumatic arthritis and of the Fiessinger-Leroy-Reiter syndrome, initiated by trauma, have been reported. Rheumatic polyarthritis and ankylosing spondylitis may also be precipitated by trauma, as shown by the two following cases:

Maurice L, aged 30, a helicopter pilot with no previous history, fell from a helicopter in 1960. Thrown from the aircraft, he sustained major trauma to his spine, but radiograms of the skeleton showed no abnormality, and in particular, no fractures. For 8 days, he had very severe pain in the thoraco-lumbar spine, with total functional incapacitation. Over the next 3 years the pain, which had regressed without totally disappearing, recurred in attacks against a permanent painful background.

In 1963, 3 years after the accident, the patient was admitted to hospital with the typical symptomatology of ankylosing spondylitis. Radiograms showed a bilateral stage II sacro-iliac arthritis, with anterior and lateral syndesmophytosis of D11/D12, D12/L1, and L4/L5.

Jean L, 56 years old, without previous history, was the victim of an aircraft accident in May 1940. He sustained very severe trauma of the spine without fracture. Persistent lumbar pain followed the trauma, with hyperalgesic episodes against a permanent background of pain which was worse at night.

In 1966, cervical pain of an inflammatory type recurred hourly.

In 1970 the patient was admitted to hospital because of persistent pain. There was a cervico-thoraco-lumbar kyphosis, with a finger to floor reach of 34 cm, a distance of 14 cm from the occiput to the wall, a chin-sternum distance of 5 cm, and chest expansion of 5 cm. Radiograms confirmed the diagnosis of ankylosing spondylitis with bilateral, stage III, sacro-iliac arthritis and ligamentary ossification in the cervical, thoracic and lumbar regions.

In fact, in ankylosing spondylitis as in other inflammatory rheumatoid conditions with initial trauma, the latter is not the primary cause of the disease. However, trauma to the spine, which is very frequent, can, it appears, occasionally be responsible for the unmasking of ankylosing spondylitis. Thus, the trauma is a contributing factor; a secondary cause (302).

8.2.2. Diagnostic Criteria

For the role of trauma in precipitating ankylosing spondylitis to be accepted, the following criteria must be met (299, 328):

1. The trauma was severe.

2. The subject was in good health before the accident.

3. The pain resulting from the trauma persists over several weeks or several months, leading to the development of ankylosing spondylitis or, perhaps, to the exacerbation of ankylosing spondylitis that had been totally quiescent.

8.3. SPONDYLOLISTHESIS AND TRAUMA

Spondylolisthesis (see 7.1.5.3.) discovered during a career poses two problems (282):

- can the condition be related to flying duties or to in-flight trauma?

- can the condition, known to exist when the patient was accepted for a flying career, develop further, and what are the medical criteria for compensation?

8.3.1. Pathological Anatomy (282, 305, 307, 331, 348, 351, 416)

The lesion in the isthmus is a gap which interrupts the continuity of the vertebra and divides it into two segments which are no longer united one with the other. Under the influence of body weight and the forces to which it is subjected, the front portion slides forward, taking with it the subjacent spine. In contrast, the posterior segment, which is restrained by the superior articular process of the vertebra immediately above, does not move (420).

Spondylolysis is a loss of bony tissue in the isthmus which is replaced by fibrous tissue uniting two regular, smooth, blunt surfaces with a normal bone structure. This fibrous tissue, dense and more or less rich in fibroblasts, often has cartilaginous inclusions in children. The change from fibrous tissue to bone is abrupt, without a transitional zone.

Thus, the breakdown of the isthmus does not have the appearance of a callus, of a pseudarthrosis, of bony necrosis, or of an area of erosion. It is accompanied by deformation of the isthmus, which is elongated, thinned and stretched, and by an abnormal mobility of the posterior arch.

8.3.2. Pathogenesis of Spondylolisthesis

With Taillard (435) we recognise four theories:

- the congenital theory, which holds that the lysis is a defect of fusion in the two centres of ossification of the posterior arch during foetal life;

- the "trophostatic" theory, which attributes the lysis to a fatigue fracture or to overload caused by a defect of geometry in the lumbar spine;

- the traumatic theory, which considers that the lysis is a symmetrical unconsolidated fracture of the isthmus;

- the theory of hereditary dysplasia, which ascribes the lysis to an anomaly in the ossification of the isthmus which progresses during growth under the combined influence of mechanical and genetic factors.

8.3.2.1. Congenital Theory

This is now no longer accepted. Several anatomical findings run against the theory:

- spondylolisthesis and spondylolysis never exist in the embryo, the foetus or the newborn;

- the posterior arch has only one centre of ossification;

- the process of ossification of the vertebral arch is like that of a diaphysis, the cartilaginous matrix being invaded by vascular branches from the vertebral canal.

The rare cases described as being congenital lysis relate to discontinuities at other sites in the vertebral arch: spina bifida occulta, fissure of the posterior arch, separation of the pedicle, disjunction between the arch and the vertebral body. The lysis is not, therefore, a true congenital malformation of the vertebral arch. Always present at birth, it appears to be determined by the action of a gene.

8.3.2.2. "Trophostatic" Theory

Formulated by Meyer-Burgdorff (1931) and adopted by Nathan (385) in 1959, this considers spondylolysis as a "slow fracture" of the isthmus brought about by chronic mechanical overloading due to hyperlordosis. While this mechanism is not common, a certain number of facts and observations provide evidence for the role of chronic overload of the isthmus.

Piwnica and Guillot (1958) (cited in 282) showed, by experimental studies on plastic models, a massive concentration of lines of force in the interarticular part of L5 under load.

Taillard (435, 436) reported two cases of lysis developing after a change of the lumbar lordosis during the period of growth, and appearing after a delay of 2-10 years following surgical operations on the spine, such as laminectomy or lumbosacral graft. He collected 15 similar observations from literature in the period 1950-1963.

The lysis is more frequent in subjects such as circus or cabaret artists who, during childhood, overstretched the movements of their lumbar spine. Moreover, spondylolysis and spondylolisthesis appear to be confined to man and his upright stance. They are not found in other mammals which otherwise have the same disorders of growth and degeneration of the spine.

This theory cannot be considered the common explanation, because it rests on observations from unusual cases. Nevertheless, the "overload factor" in the pathogenesis of spondylolisis is worthy of attention.

8.3.2.3. Traumatic Theory

Two questions must be considered:

- can trauma produce spondylolysis or spondylolisthesis in a previously normal spine?

- can trauma exacerbate a pre-existing malformation?

Post-traumatic Appearance of Spondylolysis or Spondylolisthesis

Genuine cases are rare (Newmann, Sicard, Serre, Gerard (282)). Radiograms made before the trauma demonstrate integrity of the posterior arch.

Radiograms after the trauma reveal the existence of indisputable lysis and slipping. In the dozen illustrative cases that have been published, the patients were victims of very severe trauma: a heavy fall of a parachutist (Serre (418)), a fall from the third storey of a building, serious traffic accidents (being thrown from a vehicle).

While the traumatic origin of the lysis is unquestionable in certain cases, it must be considered exceptional. It must be remembered that comparison with previous radiograms is not very convincing, because these are most often frontal and lateral views, and only paired three quarter oblique views can provide certainty.

As experimental work and large statistical studies of spinal fractures have shown, the isthmus of L5 is a very strong bony segment.

Guillemet (329) has defined the characteristics of traumatic spondylisthesis; appearance after very severe trauma; lesions similar to dislocation; fracture affecting the body, the isthmus, and sometimes the articular processes; invariable association with fractures of transverse processes (401).

Azema and Gerlach tried to produce fracture of the isthmus by means of heavy mallet blows applied to vertebral columns supported in various planes, but succeeded in breaking everything except the isthmus (282, 427).

In 823 fractures of the lumbosacral spine, Ghormley and Hofman found only 90 that involved the posterior arch of L5, and only 1 fracture of the isthmus of L5 (282, 427).

In the statistics from the Percy, Dominique Larrey and Begin Hospitals (see Chapter 5) there is no record of an isolated lesion of the isthmus of L5. Simonin (428), in a series of 727 cases of spondylolisthesis, found only one in which the traumatic origin was indisputable.

Can Trauma Aggravate a Pre-existing Malformation?

In very rare cases spondylolisthesis can appear after trauma in a subject already known to have spondylolysis of L5, or it can be exacerbated specifically by trauma (observations of Francillon, Taillard, Friberg, Sicard (282)). In the latter case, a modest increase in the slippage (of the order of 1-2 mm) may occur, which is apparently due more to a crushing of the disc of L5/S1 than to a true forward displacement of the body of L5 (438).

In contrast to these rare events, it is much more common to find that the stability of a spondylolysis or a spondylolisthesis is maintained following trauma severe enough to cause multiple fractures of neighbouring vertebral segments.

In the adult, at least, even the vertebrae affected by spondylolysis are very stable. Rarely, spondylolisthesis occurs if all the elements of the intervertebral articulation give way. Most often, the lesions of spondylolisthesis are not changed even by very severe trauma (Lance (352, 354, 355, 356)). We have had the opportunity to verify this assertion after aircraft accidents (ejection, crash) in pilots suffering from type I spondylolisthesis.

8.3.2.4. Theory of Hereditary Dysplasia

This theory, which was proposed by Neugebauer in 1881, formulated by Brocher (1951 (266)) and by Wiltse (1962 (452, 453)), and supported by Taillard, attributes the lysis to a disorder of growth of the isthmus, which ossifies in an abnormal manner under the combined influence of mechanical genetic factors. It now seems the most satisfactory concept, because it explains:

- the absence of lysis in the newborn, but its appearance and development in the infant and the adolescent; as a corollary, it permits the stability of the condition in the adult to be understood;

- the association of the lysis with other malformations, in particular of the isthmus which is attenuated or elongated;

- the relatively constant incidence in different races;

- the anthropological facts: spondylitis is only observed in man, it appears to be related to the upright posture; its development is simultaneous with that of the lumbar lordosis; it first appears when the child begins to walk;

- the site of the most commonly affected segments of the spine (L5/S1). The lysis is extremely rare in the cervical spine and does not occur at all in the thoracic segment of the vertebral column (276).

This theory allows the familial character of the disorder to be understood (Wiltse, Puck and Rogers). These authors found a higher incidence of spondylolysis in certain families and in particular ethnic groups, such as the Eskimos. (In fact, consanguinious marriages are frequent in this population.) Transmission appears to be a dominant trait, with very variable expression (Taillard (435, 436, 437).

8.3.3. Conclusions

We agree with Lance (355) that spondylolisthesis of traumatic origin occurs only in conditions so exceptional that, to be accepted, this etiology requires "a weight of proof which must be proportional to the rarity of the phenomenon" (Claude Bernard).

Exceptionally, a trauma may aggravate a spondylolisthesis of L5 on S1. We have been able to follow, through the course of their aviation career, a dozen pilots with this congenital abnormality who have had several aircraft accidents (crashes or ejections).

Trauma very frequently plays a part in precipitating a painful syndrome in a subject with a hitherto painless spondylolisthesis.

The true nature of the trauma must be established (257, 282) and subjective disability must begin to appear within a few weeks after the trauma. According to Lance (355) a completely silent interval of more than 2 months is sufficient evidence for rebutting the attribution claimed by the patient. In assessment, great importance must be attached to the data from radiological examinations, which allow the trauma to be implicated either as a cause of the initial lesion, or merely as an aggravating factor to a pre-existing lesion.

8.4. POST MORTEM RADIOGRAPHY

This is sometimes employed in the study of accidents. It can furnish valuable data which allow either the appraisal of factors that explain or determine the pathological mechanism, or the discovery of unrecognised fractures of the spine (32, 121, 168, 217). Although they may sometimes be difficult to undertake, such radiographic examinations admirably supplement the anatomico-pathological and biochemical studies (167) which are always indispensable.

CONCLUSION

The spine of a pilot or of a parachutist is exposed to two types of stress:

- stresses of relatively low intensity, the effects of which are additive and are similar to the phenomena seen in the fatigue of materials

- exceptional stresses (crash, ejection, high frequency vibration) of very high intensity, which affect the mechanical strength of the vertebral column and can lead to fractures.

The incidence, aetiological and pathological types, clinical and radiological signs, and different clinical forms of traumatic lesions of the spine in aviation should be well known to the flight surgeon. Despite the progress made in diagnosis, treatment and sometimes prophylaxis over the years, study of this important chapter in aviation medicine should still be pursued for many years to come. Variations in the flying task and the performance of new aircraft may lead to changes in the different physical, clinical and radiological aspects of traumatic injuries to the spine. The clinical and radiological studies which have so greatly advanced our knowledge should be continued, and it is highly desirable that the multi-disciplinary work which brings together clinicians, radiologists, physicians and pilots, should go on.

The study of sequelae should be promoted by better understanding on the part of flying personnel who, because they are over-anxious to preserve their fitness rating, have too great a tendency to hide the residual symptoms of vertebral trauma.

Chapter 7 shows how we can build on a single principle, valid even at the initial medical examination, by considering successive degrees of fitness which differ according to the role of the pilot (combat aircraft, transport aircraft, helicopter). We know that this point of view is not shared by all doctors and by even fewer of the headquarters staffs.

Be that as it may, radiology plays an indispensable and fundamental role. Its place in the initial medical examination, where it is now a standard procedure, is no longer in dispute. It is a *sine qua non* for the assessment of casualties, whether it be early or late.

Experimental studies should be pursued to improve the cockpit conditions in helicopters, to promote better survival in crashes, and to reduce the number of spinal fractures occurring after ejection.

ILLUSTRATIONS

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14. Abstract

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This AGARDograph presents the current views of a group of specialists in the aetiology, diagnosis and prognosis of injuries to the vertebral column resulting from flight in rotary-wing and fixed-wing aircraft and gliders, and from parachuting.

The new publication will be an indispensable aid to the work of the flight surgeon, and equally to all those concerned both with the medical surveillance of flying personnel and with flight safety.

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